Impacts of historical and projected climate changes on ice surfaces of the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

This thesis contains one manuscript that explores the relationship between climatic changes and ice road use in the Canadian arctic. Collaborations with colleagues, whether direct or indirect, aided in the submission of this paper, and are reflected below.

The manuscript as presented (Chapter 3) is the result of direct collaboration with Dr. Claude Duguay, Dr. Chris Derksen, and Dr. Laura Brown. Dr. Duguay and Dr. Derksen were heavily involved in the initial proposal of the article, and provided continuous advice and comments throughout the duration of the study. Dr. Brown was instrumental in the data processing and analysis stage of the research, and made herself available to countless questions and concerns regarding the CLIMo data used for this study. All three will continue to be involved throughout the submission and revision process, and will be listed as co-authors on any future published works derived from this thesis.

ABSTRACT

Seasonal ice and winter roads are a historically important part of the Canadian arctic transportation network. Constructed over frozen lakes, rivers, permafrost zones, and seasonally frozen ground, the roads service rural and aboriginal communities and resource extraction projects which are otherwise fly-in only for the rest of the year. The Tibbitt to Contwoyto Winter Road (TCWR) is one of the most economically significant and heavily used roads, running from outside of Yellowknife, Northwest Territories, to Contwoyto Lake, Nunavut, connecting three of Canada's largest diamond mines, with a fourth project set to open on route by 2017. The TCWR has been constructed annually since 1982 as a joint venture between mine operators Diavik Diamond Mines Inc., BHB Billiton Diamonds Inc., and DeBeers Canada Inc., and requires a minimum ice thickness of 0.7 m to begin operations, with an average open season of 67 days. Current projections suggest an arctic amplification of the global climate warming signal, as well as changes to arctic precipitation patterns. Both have the potential to alter lake ice conditions, with economic impacts for the long-term viability of ice roads for moving mine supplies north via land.

This thesis uses a one-dimensional thermodynamic lake ice model (Canadian Lake Ice Model – CLIMo), forced with atmospheric reanalysis data (ERA-Interim) to simulate historical ice conditions, as well as regional climate model outputs (Canadian Regional Climate Model – CRCM 4.2.0), to make near-future projections for ice phenology and thickness trends. Using road opening and closing dates provided by road managers, we model the historical variability in ice phenologies for the known operations period 1982-2011, as well as future conditions for the period 2041-2070 compared against a 1961-1990 baseline for a future climate scenario based on IPCC SRES scenario A2.

Model runs suggest that climatic changes in the arctic, primarily warming surface air temperatures, could pose a threat to continued operations of the TCWR. A Mann-Kendall test is paired with the Sen's Slope method for analysis on the historical data, finding that the ice cover season may have decreased by as much as 10 days between 1982 and 2011 (significant at the 0.05 level), and mean maximum ice thickness may have decreased by as much as 0.17 m over the same period (significant at the 0.05 level). CLIMo simulations for future climate scenarios project later ice-on dates by up to 11 days later in the calendar year, ice-off events occurring up to 14 days earlier in the spring, and a net decrease in the ice cover season by up to 25 days (after

rounding), when computed as the difference between the 1961-1990 baseline and 2041-2070 future period. Mean maximum ice thickness is projected to decrease by up to 0.30 m over the same period. While winter ice cover is unlikely to disappear entirely in the near future, the number of days where the ice surface is consistently above the 0.7 m threshold for safe operations may decrease to the point where it no longer becomes economically feasible to build the road and transport materials via land.

ACKNOWLEDGEMENTS

I am beyond fortunate to have had such incredible personal and academic support over these last two years. It is so clear to me that this achievement is far from mine alone. I hope I can repay the many favours someday.

Much love, and gratitude,

Erika

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CHAPTER 1: INTRODUCTION

1.1 Overview

There is a wealth of evidence suggesting that the global climate is changing rapidly. These changes will not be felt uniformly across the globe, however, with the arctic polar region currently projected to see greater-than-average changes and variability in future climate scenarios, via a culmination of processes known as arctic amplification. These magnified changes have the potential to dramatically impact natural and human activities in the region. Much work has been done exploring possible changes to physical processes (climatological, hydrological, ecological, and other), and a growing body of work is emerging to discuss the implications for human activities in the far north. This thesis will contribute to the field by focusing on the realm of arctic transportation. It is well-understood that a warmer arctic will dramatically increase the potential for use of marine transportation routes, for example via ice-free summer seasons in the northern shipping channels; however, there is evidence that the trend will be reversed for overland transportation systems. Contrary to marine shipping, which relies on ice-free or thin ice conditions in the summer months, overland transportation occurs almost exclusively in the winter and relies on solid permafrost and thick river and lake ice conditions on which to build temporary road networks. Given the current understanding of climate trends at high latitudes, it stands to reason that a changing climate may affect the viability of overland transportation in the future.

1.2 Context and rationale

Ice roads (typically defined as built over frozen water) and winter roads (typically defined as built over frozen land, or as encompassing a combination of the two) are an important feature of Canada's arctic infrastructure program. Much of the Canadian tundra is a water-rich landscape, upon which building permanent infrastructure is an engineering challenge. However, many rural and aboriginal communities exist and continue to grow across the region and require that people and goods be moved in and out. As well, the north is home to several economically significant resource extraction projects which rely on temporary winter roads to move heavy and costly goods to continue operations. These projects allow road access, if only seasonally, to communities and resource extraction projects that are fly-in only for the rest of the year.

Transportation in the arctic becomes an especially important question in the face of the increased attention paid to the region in terms of national political interest and economic expansion. The region is projected to store significant oil and gas reserves; the reserves may be more easily extracted under warming climate scenarios. However, expansion will require an increase in the spatial extent of the overland infrastructure network, the availability of which currently exist is negatively correlated with warming temperatures. For extraction to increase, the capacity to move goods and people in and out of the region cost effectively and efficiently must do the same.

Given the volatility and vulnerability of winter roads, a large body of research has also gone towards building all-season road networks. The challenge in building all-season roads lies primarily in building permanent structures on a dynamic landscape. The freeze-thaw patterns of the lowland bog and fen systems, lakes, and shifting permafrost and seasonally frozen ground, provide little stability for permanent roads. Many of these routes also run through ecologically sensitive areas which could sustain significant damage if open to road traffic year-round. However, due to the high cost of and logistical difficulties of rebuilding ice roads every winter season, much research has been put into the development of all-season roads. In particular, progress is being made in the Mackenzie Valley region, with plans in place to expand the Dempster Highway through to Tuktoyuktuk, Northwest Territories. After many delays, construction has currently begun on the leg from Inuvik to Tuktoyuktuk; a completion date of 2018 has tentatively been set. Until all-season roads can be built reliably across the wide variety of arctic and sub-arctic landscape that winter roads currently traverse, seasonal roads will continue to be a relevant area of study and exploration.

While there are merits to studying the breadth of the continuum of arctic seasonal infrastructure, this thesis will focus on roads serving industrial projects, due their size, history, and economic significance. Specifically, it will look at the Tibbitt-to-Contwoyto Winter Road (TCWR), a large-scale annual road project that connects three of Canada's largest diamond mines. The TCWR runs for over 400 km through the Northwest Territories, starting at the end of the Ingraham Trail (the region's northernmost all-season road) outside of Yellowknife, to the now-defunct Lupin Mine in Nunavut. The road has been constructed annually since 1982. Eighty-seven per cent of the road is constructed over frozen lakes, with 64 land portages. Unlike many seasonal roads in the region, which are government-run and maintained, the TCWR is privately constructed and managed by a consortium between the three companies who run mines which are serviced by the road. Currently, the TCWR services the Snap Lake Mine (BHP Billiton Diamonds Inc.), Diavik Diamond Mine (Diavik Diamond Mines Inc), and the Ekati Diamond Mine (BHP Billiton Diamonds Inc). The three operating companies have together formed the Joint Venture Management Committee (JVMC) to oversee the project. The unique size and scope of the TCWR has brought it international attention on the History Channel reality television show, *Ice Road Truckers*, which follows a group of truck drivers who make their living on the road for a few dangerous months every year.

1.3 Objectives

This thesis has two primary objectives. First, it seeks to inform broadly the trends in Canadian arctic lake ice regimes in the context of overland transportation methods. Advances in how we understand climate change, particularly in the polar regions and in climate modeling, make it possible to force physical process models with more accurate climate data to get a comprehensive picture of our climatic future. The Canadian arctic is a region experiencing rapid climatic change when compared to 20th-century baselines, with significance for natural processes and life, as well as the communities building homes there, and companies building livelihoods. The region is also on the frontier of national political and economic expansion, both of which stand to be significantly impacted as climatic conditions shift.

Towards this goal, the Canadian Lake Ice Model (CLIMo) is first forced with atmospheric reanalysis data for the historical operation period (1982-2011) to compare ice regimes with road season data. Anomalously long and short seasons are identified and their significance discussed. The variability of four key indicators of ice conditions — ice-on dates, ice-off dates, ice season duration, and maximum ice thickness — is studied temporally and spatially and implications for future operations are addressed.

The second objective is to shift away from generalized discussions of historical conditions towards projections of future ice conditions that could inform road planning exercises in the near future. To facilitate this, CLIMo is forced with regional climate model inputs, and a 30-year baseline period is compared with a 30-year future period to determine broad trends in maximum ice thickness, ice cover duration, and ice-off and ice-on dates. These indicators are then applied to known operational standards the Tibbitt to Contwoyto Winter Road to make inferences about its continued viability in a warmer arctic.

1.4 Structure

The structure of this thesis is as follows: first, a literature review section, elaborating on the history of ice roads for Canadian polar transportation, as well as relevant climate–lake ice interactions, followed by a discussion of the study site and methods employed, including a review of the models and input datasets used (Chapter 2). Chapter 3 will present original research using the Canadian Lake Ice Model forced with atmospheric reanalysis data and regional climate model output and discuss the implications of changing ice regimes on the ice surfaces of the Tibbitt-to-Contwoyto Winter Road. Finally, the thesis will offer concluding remarks, including study limitations and the potential for future work (Chapter 4).

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

This section will provide an overview of the concepts, methods, and literature relevant to the research conducted for the body of the thesis. First, it will summarize the history and use of ice roads in the Canadian arctic. Second, it will review how the scientific community currently understands observed and projected changes in the arctic climate system. Third, it will review temperature and precipitation-driven lake ice processes and known sensitivities. Finally, it will review the models used to make the historical and future ice condition simulations for this thesis, and the input datasets used to drive the models.

2.1 History of ice roads in the Canadian arctic

Little academic literature currently exists regarding the state or breadth of Canada's winter and ice road networks. Ice roads (typically defined as built over frozen lakes and rivers) and winter roads (typically defined as built over permafrost or seasonally frozen ground) are currently used extensively across Nunavut, the Yukon, and the Northwest Territories (Figure 2-1), as well as northern Alberta , Saskatchewan, Manitoba, Ontario, Quebec, and Labrador (Newfoundland) . The roads are most often built and maintained by provincial and territorial governments, and connect northern rural and aboriginal communities and resource extraction projects with southern all-season roadways. While much energy has been put towards understanding the future of arctic marine transport routes (e.g. shipping via the Northwest Passage) under warming climate scenarios, the impacts of climate changes on overland transportation remain poorly understood, sporadically documented, and often researched out of context of the broader network. For example, as transportation in Canada is managed provincially and territorially, there is no single database of all Canadian ice roads in current or historical use. The matter is complicated by the fact that in addition to government-run roads, projects such as the Tibbitt to Contwoyto Winter Road (TCWR) exist under private jurisdiction, and thus are especially easily overlooked.

Figure 2-1: Map of Northwest Territories highway and winter road system (GNWT Department of Transportation, n.d.) . Most of the arctic region is undeveloped, and communities and industrial projects that exist outside of the limited road framework are typically fly-in only during the summer months when the landscape is unfrozen.

The fragmented nature of ice road management means that available research into the field is equally patchy. Much of the knowledge is currently held internally, usually by the firms which build the roads, or published informally as grey literature from provincial and territorial governments, or via industry conferences. What is known, though admittedly anecdotally, is that much of the Canadian arctic is inaccessible except by air for much of the year, and it stands to reason that increasing this period of relative inaccessibility due to climate change will not happen without consequence for the communities, aboriginal groups, and industrial projects that rely on seasonal road access to maintain operations (Prowse et al., 2009; Prowse et al., 2011a; Prowse et al., 2011b).

In one of the first major publications on arctic overland transportation, Stephenson et al. (2012) use a modeling framework to discuss how projected climate changes will impact critical transportation networks across the world's arctic polar countries, including Canada's estimated 5,400 kilometres of seasonal roads. Using the metric of 'winter-road accessible land area' (defined for the construction season of October to April), the authors find that almost 400,000 square kilometres of the Canadian subarctic may become unusable for winter road construction by 2045-2059 (-13%), if warming trends continue at the present rate (Stephenson et al., 2012). Global losses are projected at 14 per cent, in contrast with a 24 per cent increase in marine accessible areas if current exclusive economic zones remain stable (2012). Via temporal metrics, Stephenson et al. (2012) also project that the TCWR will lose 17 per cent of its operating season between 2008 and 2020.

The Arctic Monitoring and Assessment Program (AMAP), an intergovernmental council composed of researchers from arctic countries, produced the comprehensive Snow, Water, Ice, Permafrost in the Arctic (SWIPA) report in 2011, detailing the changes observed across cryospheric elements of the climate system and the implications for human activities due to these changes. References were made throughout to challenges in building ice roads in a warmer climate, given thinner ice cover and shorter ice cover seasons, and a decrease in the area of the continuous permafrost zone (SWIPA, 2011); however, specific roads were not studied in detail, and changes as a whole were not quantified. The report suggested that continued warming could preclude the use of ice roads for arctic transportation in the future, and acknowledges the necessity of these roads given the increased economic activity taking place north of 60N, and the rate at which this trend is expected to continue (SWIPA, 2011). The Government of Manitoba (2009) calculates that its spending on winter road maintenance has tripled since 1999, and over 600 kilometres of former seasonal roads have been discontinued or reconstructed as all-season roads. Notably the report discusses at length the challenges associated in mitigating or adapting to changes in freshwater ice cover due to the lack of certainty surrounding how arctic permafrost will continue to change in tandem (SWIPA, 2011).

Given the increasing evidence that global climate change will shorten the natural ice road season, much work is also being put towards the development of all-season roads in the far north. Progress has been made on extending the all-season Mackenzie Valley Highway from Wrigley, NWT, to join with the all-weather Dempster Highway at Inuvik, with the addition of a permanent connection between Inuvik and Tuktoyuktuk, on the Beaufort Sea (GNWT Mackenzie Valley Highway, 2013). Construction has commenced on the section from Inuvik to Tuktoyuktuk, with a tentative completion date scheduled for winter 2018.

The challenge in building all-season roads in the arctic lies in the instability of the landscape: much of the subarctic and high arctic landscape is dominated by organic deposits (as fens, bogs, marshes, peatlands, et cetera) and has a high proportion of surface water, and seasonal freeze-thaw patterns make building permanent structures unpredictable and difficult. In regions of continuous permafrost, engineers must take into consideration how road construction and use will affect the permafrost; the Inuvik to Tuktoyuktuk highway will be built at least 1.8 metres above ground to limit the potential for use to thaw the permafrost and cause structural damage (GNWT Department of Transportation, n.d.). Some sinkage is expected, in which case engineers will fill the landscape with gravel and other granular material until it reaches its steady state (GNWT Department of Transportation, n.d.).

At present, no studies have been made public regarding the potential for all-weather road construction in the region of the Tibbitt to Contwoyto Winter Road, the focus point for this thesis. The Tibbitt-to-Contwoyto Winter Road (TCWR) runs from outside of Yellowknife, Northwest Territories, to Contwoyto Lake, Nunavut (Figure 2-2). The region is lake-rich, with an estimated 40 per cent of the surface covered by water (Mackay et al., 2009). The mean lake depth along the road is estimated to be between 1.76 m (Macumber et al., 2012) and 8.2 m (Pienitz et al., 1997). It has been constructed annually along the same route since 1982. In line with the high proportion of surface water, 87 per cent of the road is constructed over frozen lakes, with the remaining 13 per cent constructed over 64 land portages. The majority of seasonal roads in Canada are government-run and maintained; however the TCWR is privately constructed and managed by a consortium between the three companies who run mines which are serviced by the road. Currently, the TCWR services the Snap Lake Mine (BHP Billiton Diamonds Inc.), Diavik Diamond Mine (Diavik Diamond Mines Inc), and the Ekati Diamond Mine (BHP Billiton Diamonds Inc). A fourth mining project operated by DeBeers, the Gaucho Kue project, is set to open on route by 2017. The three operating companies have together formed the Joint Venture Management Committee (JVMC) to oversee the project.

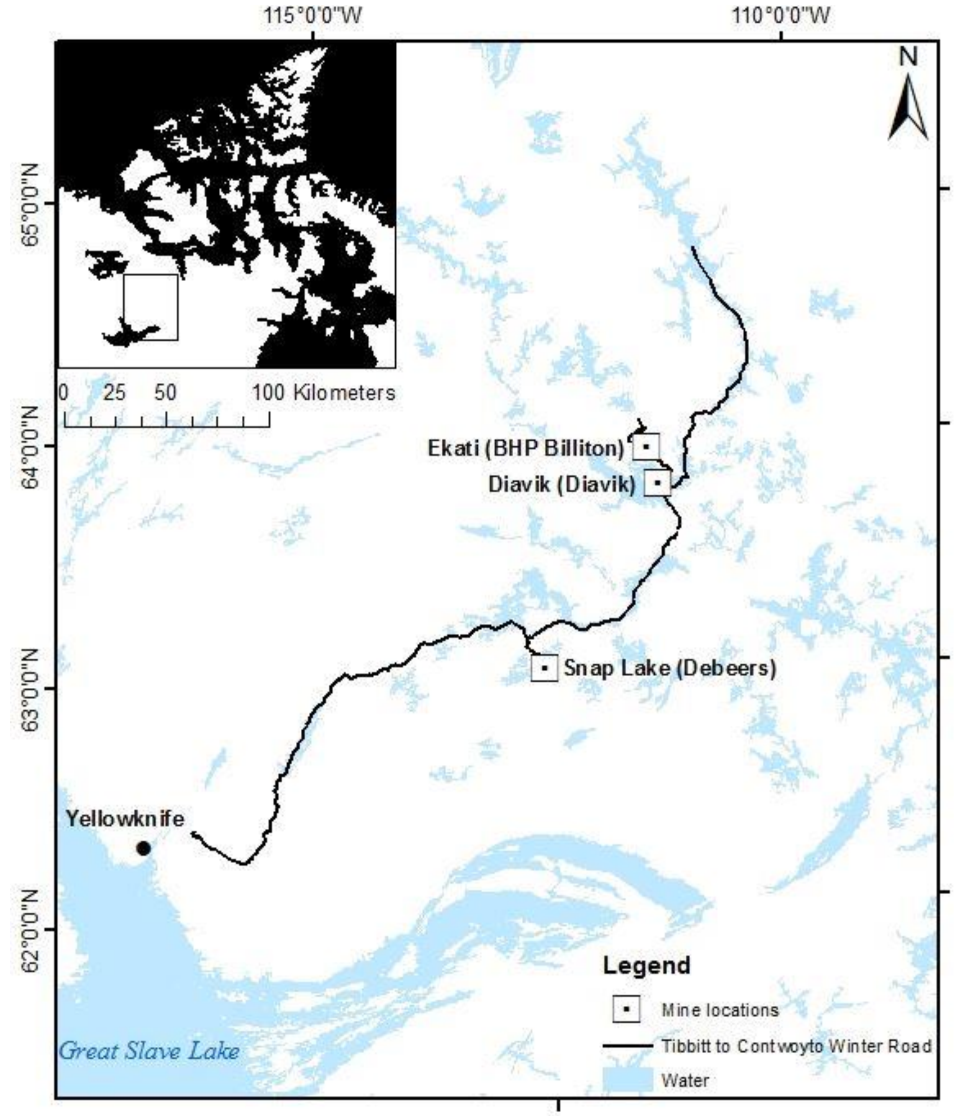


Figure 2-2: Map of the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada

2.2 Arctic climate changes

2.2.1 Observed

The arctic climate system is changing rapidly, across all indicators, when compared against a late-20th century baseline period (NOAA Arctic Report Card, 2013).

Surface air temperature trends for the early part of the 21st century are consistently warmer than the 1971-2000 mean period, with positive temperature anomalies occurring across the region, often in excess of 2C (see Figure 2-3). When broken down across the year, warming trends are consistently observed across all seasons, with the largest anomalies occurring in September through February (Derksen et al., 2012; Serreze & Barry, 2011). Arctic surface air temperatures show strong relationships to sea ice extent. For example, fall 2012 was anomalously warm in response to the record summer sea ice minimum observed in September of the same year, due to the large sensible heat flux from the open water area (NOAA Arctic Report Card, 2013). Winter temperatures are in turn related to summer sea ice extent and fall temperatures, while spring anomalies are often explainable by temperature patterns during the proceeding winter, as well as trends in precipitation regimes (i.e. snow fall and snow cover extent), which influence surface albedo and earth-atmosphere and ocean-atmosphere sensible and latent heat fluxes.

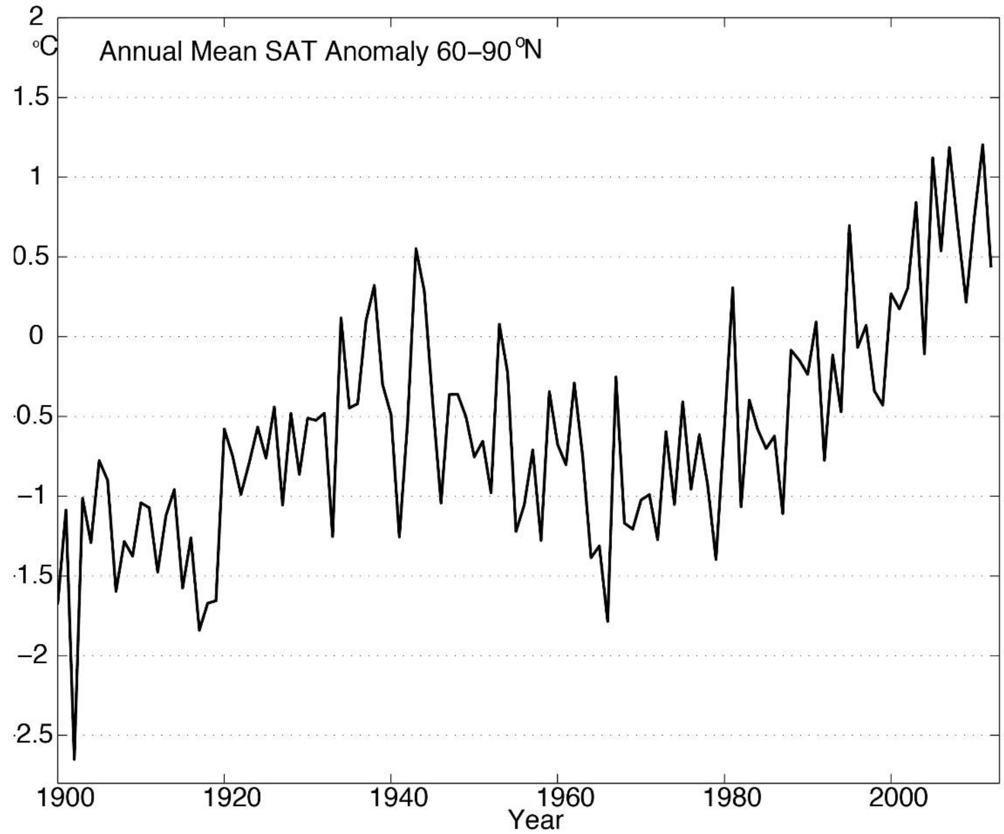


Figure 2-3: Arctic surface air temperature anomalies from 1900 to 2010, compared against the 1981-2010 baseline period, showing a trend towards warmer temperatures in the 21st century (NOAA Arctic Report Card: air temperature, 2013).

The arctic cryosphere is also exhibiting a perceptible response to the warming trend. Snow cover extent continues to show a downward trend, with losses of 19.9 per cent per decade compared to the 1981-2010 mean (NOAA Arctic Report Card, 2013). Significant trends are seen towards decreases in both the annual arctic sea ice maximums and minimums, with further trends towards less multi-year ice, and more first-year sea ice (NOAA Arctic Report Card, 2013). The lowest sea ice minimum on record occurred in 2012, followed by 2007 and 2011 (NOAA Arctic Report Card, 2013). There is evidence that the boundary of the continuous permafrost zone is shifting northward (SWIPA, 2011), with a related 'greening' of the arctic occurring as the tree line responds to changing soil conditions (NOAA Arctic Report Card, 2013).

Arctic freshwater ice has also been observed to be responding to regional climatic changes. Lake and river ice is known to be sensitive to climatic changes; the time series can be noisy, but studies show decreases in the ice-cover season via delays in fall ice-on and earlier spring ice-off dates, as well as decreases to the ice thickness (NOAA Arctic Report Card, 2013). Bonsal et al. (2006) explored the connection between arctic freshwater ice and atmospheric teleconnections. Strong relationships were found between ice cover duration and the Pacific Decadal Oscillation and the Pacific–North American pattern. Understanding these atmospheric flow patterns and the different temporal and spatial scales on which they operate and how they interact with other warming mechanisms will remain important in the future as warming trends continue. Atmospheric teleconnections are understood to influence many facets of the arctic climate system (sea ice and snow cover, especially (Stroeve et al., 2012; Rigor et al., 2002; Overland and Wang, 2005), in addition to lake and river ice regimes.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) includes a brief section on observed changes to freshwater ice cover; however, the report acknowledges the lack of cohesive data available and subsequent difficulty in constructing trends (IPCC AR5, 2013). The review concludes that based on the limited data available, it appears that ice seasons are shortening, ice-on dates are occurring later in the year, and ice-off events are occurring earlier (however, with significant spatial variability). The rates of changes appear to be higher in recent periods and at higher latitudes, and quantitatively related to air temperature changes (IPCC AR5, 2013).

2.2.2 Projected

Both the observed and projected arctic warming signals lend credence to the theory of 'arctic amplification', which is defined as temperature anomalies greater than 1.5C when compared to lower latitudes (Stroeve et al., 2011; Walsh et al., 2012).

Arctic amplification has been well-documented and discussed (Lesins et al., 2012; Serreze & Barry, 2011) in the context of the greater-than-average warming trends exhibited in this region. While arctic amplification is understood as a combination of processes, current research largely focuses on the relationship between temperatures and the positive surface albedo feedback: increasing surface air temperatures will melt some of the arctic's highly reflective snow and ice surfaces, decreasing the region's net albedo and exacerbating the warming trend.

Winton (2006) finds a mean annual arctic (60-90N) warming of 1.9 times the global mean warming at the time of carbon dioxide emissions doubling.

Arctic ice and snow surfaces are projected to change in tandem with air temperature trends. The sea ice literature is largely in agreement that the arctic will be ice-free in the summer by 2100, with early estimates as soon as 2030-2050, depending on the modeling framework and parameters applied (Holland et al., 2006; Overland & Wang, 2013; Stroeve et al., 2007; Wang & Overland, 2009). Studies suggest that a mean warming of 2C is necessary for ice-free summers by the end of the century (Mahlstein & Knutti, 2012), which falls within the scientifically accepted range of projected temperature changes.

Snow cover accumulation and extent are projected to decrease towards the end of the century, in response to changing arctic precipitation patterns, as well as temperature changes. Snow accumulation is projected to begin later in the year, and melt earlier (Slater & Lawrence, 2009; 2012). Patterns of accumulation remain unclear, however; there is uncertainty regarding the significance of warming surface air temperatures reducing the proportion of precipitation that will fall as snow, versus the increased moisture availability via the increased latent heat fluxes over the Arctic Ocean over a larger ice-free area (Liu et al., 2011). Similarly, the continuous permafrost zone is expected to continue to shift northwards, with significant degradation of the permafrost layer, and a thicker active (thaw) layer (IPCC AR5, 2013).

Studies also show that arctic lake ice cover will continue to change in response to climate warming, in line with its high observed sensitivity to temperature and precipitation changes. Brown and Duguay (2011) modelled lake ice cover across the Canadian arctic for a late-21st century future period, for two climate scenarios based on IPCC SRES scenario A2 (based on continually increasing greenhouse gas emissions), finding changes in ice phenologies and thickness across much of the region. In particular, the results suggest average delays in ice-on events of five to 15 days across the Canadian mainland arctic, and earlier ice-off events of five to 20 days, depending on lake depth and latitude (Brown and Duguay, 2011). The changes to ice-on and ice-off dates combine for a net decrease in the ice cover season, by 10 to 35 days, again dependent on regional physiographic features. Maximum ice thickness was also shown to decrease over the future period, by 0.10 to 0.20 metres across the region (Brown and Duguay, 2011).

2.2.3 Implications for ice road construction and use

Lakes both respond to and influence weather and climate on local and regional scales (Derksen et al., 2012). In particular, lakes are known to impact thermal regimes, water balances, and biogeochemical cycles of northern regions (Derksen et al., 2012). The significance of freshwater ice for the climate is dependent on several factors, including the timing of the fall freeze-up and spring thaw, length of ice season, and the size and location of the water body (Prowse et al., 2012b). Lakes appear to be highly sensitive to inter- and intra-annual climate variability, making them good indicators of broader climate change (Rouse et al., 2008). This holds especially true in northern latitudes, where ice cover is being shown to change dramatically in the onset of amplified arctic climate change.

The primary questions regarding the long-term utility of ice roads in the Canadian arctic are whether or not ice will continue to reach the required thickness, and in the case of the TCWR, if the ice will maintain the necessary thickness for long enough periods of time and across a large enough area to justify the high annual costs to build it (estimated at $10 million per year) (SWIPA, 2011).

There are many potential metrics by which to compare ice road utility in the future. Stephenson et al. (2012) use a transportation model to determine the rate of change of the total "winter road accessible area", or the areal extent on which a road could potentially be built; however they do not discuss temporal changes within the operations season. This thesis presents results for changes in ice cover thickness and changes in ice season length as gridded model output to capture spatial and temporal change. This is important especially due to the high sensitivity of freshwater ice response to its climate, and the high degree of variability observed in lake ice datasets. The trends at the beginning and end of the ice season, when the temperatures hover around freezing, are highly uncertain and exhibit considerable variability, and ice growth is highly sensitive to temperature changes during these periods, when even a one-degree change can delay ice-on or accelerate ice-off by days or even weeks. Ice road managers are in turn cautious when building the roads and organizing operations, due to the high risk for the personnel using the roads to transport materials. The climatic considerations with greatest effect on the continued use of ice roads are the high degree of uncertainty regarding projected changes and rates of change for arctic freshwater ice; the high sensitivity of freshwater ice to temperature and precipitation pattern changes; and the high degree of variability of responses and noisy datasets that make it difficult to determine spatial and temporal trends.

2.4 Sensitivity of arctic lake ice to climate

The sensitivity of lake ice to climate is well-documented and integrated into modeling frameworks. In particular, the literature focuses on the impacts of: 1) seasonality, or the timing of temperature anomalies; 2) snow cover on the ice surface/changes to precipitation regimes; 3) lake size; and 4) lake latitude. These drivers are studied in the context of changes in surface air temperatures and precipitation regimes, which are well-understood as being the primary drivers of ice growth and decay.

2.4.1 Seasonality and the timing of climate anomalies

The literature suggests that one of the simplest, but most significant determinants of the sensitivity of lake ice to climate variability is the timing and magnitude of the temperature or precipitation anomalies.

It is both intuitive and validated that ice surfaces will respond differently to temperature anomalies at different times of the year. Liston and Hall (1995a; 1995b) demonstrated via an early modeling framework that the growth curve of high latitude lake ice is steeper at ice-off and ice-on, with ice surfaces gaining and losing mass more quickly in response to small changes in temperatures at the beginning and end of the ice cover season.

This has been corroborated more recently with modeling and non-modeling approaches. Ménard et al. (2002) used the Canadian Lake Ice Model (CLIMo) to demonstrate a similar time-dependent sensitivity for lakes in the Canadian arctic, and Bonsal et al. (2006) and Duguay et al., (2006) have dedicated much time to linking historical movement of the zero-degree isotherm – the latitudinal line of equal surface air temperature dividing freezing from positive temperatures – to ice-off dates, finding that the two are closely linked, suggesting that lake ice is sensitive on the order of one degree to temperature changes at the end of the season. Bonsal et al (2006). demonstrate via historical climate records that ice-off events in the Canadian arctic can be delayed by up to two weeks by temperatures only 0.5C cooler than average.

Seasonality is also significant when comparing trends between ice-off and ice-on, due to the different drivers affecting both processes. Bonsal et al. (2006) and Duguay et al. (2006) demonstrated that ice-off events are more sensitive to temperature than are ice-on events. This is validated by the heat storage mechanisms explained by Rouse et al. (2005) and Oswald and Rouse (2004). Lake ice-on is closely related to lake size and heat storage capacity, and is thusly more dependent on climatic conditions earlier in the year. Conversely, ice-off occurs independent of stored energy within the water, and water temperatures are relatively constant across the size gradient, making ice-off dependent primarily on the immediate surface air temperatures.

Finally, precipitation regimes (especially snow in high latitudes) affect the sensitivity of lake ice responses, but are generally of secondary importance to temperature. Snow cover cannot impact ice surfaces during ice-on (snow cannot interact with an ice surface that has not formed yet), but the insulating properties of snow mean a snow layer on a newly formed ice surface can impede the evolution of ice thickness throughout the season (Liston and Hall 1995a; 1995b; Ménard et al., 2002; Brown and Duguay, 2011), and that a snow layer present on the ice surface around the time of ice-off, or timing of above-freezing temperatures can delay ice-off, but the magnitude of this impact has not been firmly established (Ménard et al., 2002).

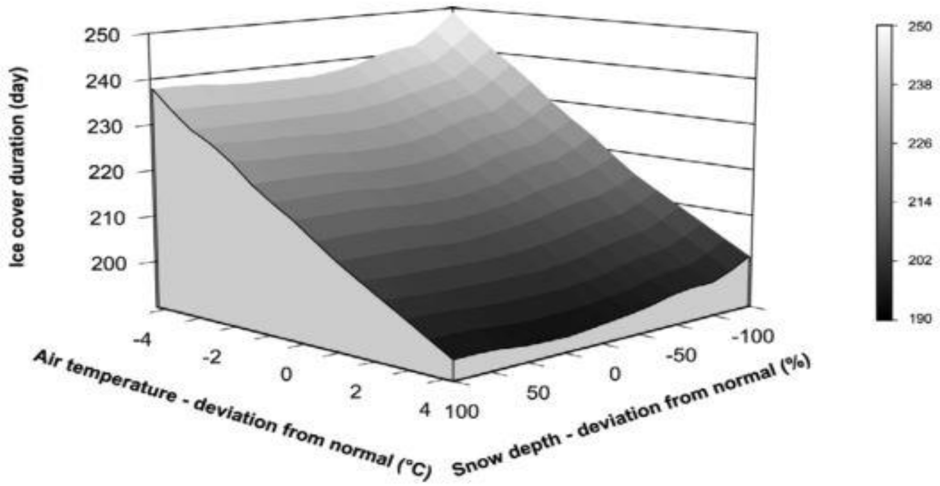
2.4.2 Snow cover

Snow plays an important role in the determining the sensitivity of ice surfaces to climate variability, in terms of the timing of the snow event, as well as quantity and type of snowfall.

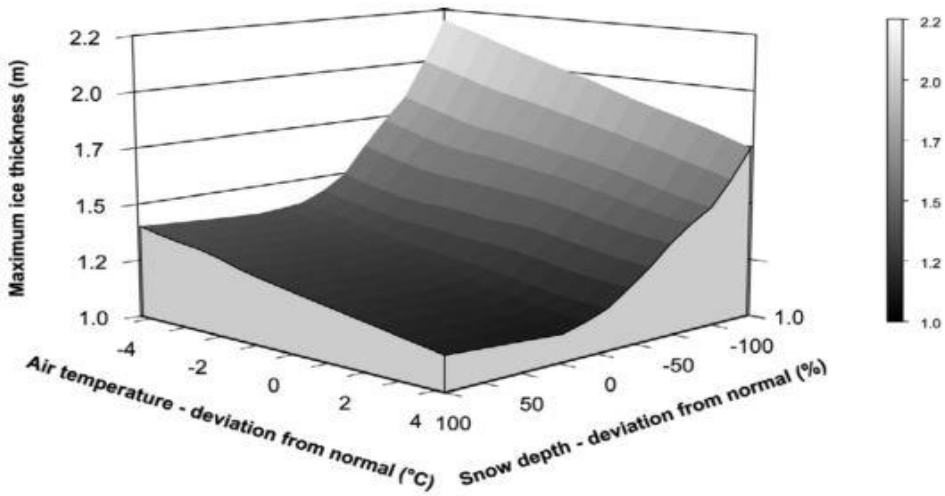
The dominant effect of a snow layer on an ice surface is its insulating properties and ability to retard ice growth and decay (see: Brown & Duguay, 2010; 2011; Liston & Hall, 1995a; 1995b; Sturm, 2002; Riche & Schneebeli, 2013) . In early lake ice modeling experiments, Liston and Hall (1995a; 1995b) ran simulations of ice growth with and without a snow layer; in all simulations, the mean maximum thickness achieved when snow was present on the ice was less than in model runs where snow was removed. This has been validated with in situ observations, and is seen across the cryosphere, including arctic and antarctic sea ice, with applications for permafrost distribution as well. However, studies indicate that snow does not insulate uniformly. There are many distinctions in snow layer properties which can affect how the snow layer will interact with ice phenologies, with the predominant considerations being depth and density of the snowpack (Adams, 1976; Duguay et al., 2002; Duguay et al., 2003; Jeffries et al., 2005). Finally, climatic controls such as wind direction and speed can influence the capacity of snow to insulate an ice surface. Wind can either remove or accumulate snow across a surface; compacted snow typically exhibits a higher thermal conductivity, which allows for greater heat loss at the snow–ice interface, and therefore increased ice thickness (Bengtsson, 1986).

The second consideration for the influence of snow on the ice surface is that at sufficient quantities of snow can increase ice growth through a process known as ‘slushing’. When the snow layer reaches a certain weight threshold, it is possible to depress the ice below the water surface, where it can then flood and refreeze as ‘snow ice’ or ‘white ice’ (Adams, 1976). The results have been observed and validated across arctic and Antarctic sea ice floes, as well as on lake ice. Snow ice formation has also been incorporated into many significant lake ice models, including the Canadian Lake Ice Model, MyLake, and Flake (see: Brown & Duguay, 2011; Dibike et al., 2011; Mironov, 2008).

It is important to note, however, that the insulating abilities of snow far outweigh its potential for snow ice formation in the arctic regions. Liston and Hall’s sensitivity analysis (1995a) and Ménard et al.’s analysis of ice formation on Great Slave Lake, NWT, Canada (2003), show that the removal of all snow cover can affect maximum thickness by almost one metre, while increasing snow cover to force slushing will increase thickness by only 0.10 to 0.20 m, compared to baseline conditions.



2-4a Impact of changes in air temperature and snow depth on ice cover duration, Back Bay (Great Slave Lake).



2-4b Impact of changes in air temperature and snow depth on maximum ice thickness, Back Bay (Great Slave Lake).

Figure 2-4: Ice cover season (top) and thickness (bottom) change in response to temperature and precipitation anomalies, showing that season length is primarily affected by surface air temperatures, while thickness is determined by the presence or absence of snow (Ménard et al., 2002).

2.4.3 Lake size

Lake size is a principal determinant of lake ice sensitivity due to the high heat storage potential of water. The influence of lake size has been studied extensively, in many contexts, including the role of lakes in regional energy budgets, local and regional climates, and climate-lake interactions. The keys questions to address in terms of sensitivity are whether lake ice will respond evenly to climate changes across a size gradient, what aspect of size (surface area versus depth) appears to be the most significant, and what factors determine how size influences sensitivity.

Williams et al. (2004) argue that while the surface area of a lake influences how ice forms and decays, the statistical relationships are weak and only loosely related to the climatic variables of temperature and snow cover. Lakes with a larger surface area are likely to experience greater wind speeds which could affect snow accumulation patterns. As well, the greater wind speeds may cause later ice-on dates by breaking up thin, early-forming ice several times before a strong ice cover can take hold. At the other end of the season, stronger winds may cause earlier ice-off dates by adding a dynamic component to ice-off, on top of the pre-existing thermodynamic processes. Williams et al. also discuss the possibility that stronger winds may increase heat transfers in the fall, accelerating the cooling process leading to earlier ice-on dates.

Lake depth has been shown to be a significant determinant of lake ice regimes through the study of the energy budgets of lakes and lake-rich regions. Rouse et al. (2005) consider sub-arctic landscapes in the context of the role of lakes on surface energy budgets; the study focuses on comparing components of the basic surface energy budget (net radiation equals the sum of the sensible, latent, and ground fluxes, plus a heat storage term) for large, medium, and small lakes (determined by depth), as well as a control ‘dry’ landscape. Their results show that large lakes have much larger heat storage terms, and heat storage in these large lakes peaks late in the season. Large lakes also have relatively small sensible heat fluxes, with the largest transfer of energy via the latent fluxes. It is also important to note that due to the very large heat storage potential in large lakes, the evaporative fluxes build consistently across the season, completing in the late fall, at a time when most small and medium lakes have no remaining stored energy and have long since experience ice-on events. Lakes of all sizes in this region exhibit insignificant conductive ground fluxes. Rouse et al. (2005) find no significant trends in lake depth in regards to ice-off events.

Large lakes are less sensitive to short-term climatic variability during the fall ice-on period, as large lakes exhibit ice-on dates well beyond when surface air temperatures fall below zero degrees, the small temperature shifts which may significantly alter ice-on dates in smaller lakes (Bonsal et al., 2006) will have little to no effect on deeper water bodies. The sensitivity of ice responses at ice-off is not affected by lake depth.

2.4.4 Lake latitude

Until the mid-2000s, most studies took a simplified view of the lake ice-latitude relationship, assuming a linear relationship between latitude and ice on and off dates (Williams et al., 2004; Raab & Vedin, 1995). Over large scales this relationship holds largely true; however, over smaller scales physiographic features, such as water bodies or elevation changes, can have the dominant effects on climate patterns.

The longer a lake spends around 0C, the more variable its response to temperature changes will be (Weyehmeyer et al., 2010; Weyehmeyer et al., 2004; Liston & Hall, 1995a). Lakes at higher latitudes are significantly less sensitive to one-degree temperature changes than are lakes at more southern latitudes, on the order of a four-day advance in ice-off compared to 14 days. This relates closely to the variability in responses at different latitudes, including the variability of ice-off events between more northern and southern lakes. Weyhenmeyer et al.'s (2004) comparison between satellite records and historical climate data suggests that lakes at more southern latitude experience more natural variability, which may make it harder to interpret trends over recent climatic conditions. While there are relatively few papers on the relationship between lake ice sensitivity and latitude, that sensitivity is not uniform across latitudes appears to have been generally accepted and cited by most prominent lake ice groups currently publishing.

2.5 Lake ice modeling: model and data used in this thesis

Numerical modeling has become increasingly common as a tool to study lakes and lake ice regimes, especially at high latitudes, where regularly collecting observational data may be impractical, and as the number of observation stations across the arctic continues to decrease. Models are also especially useful for projecting changes to future conditions, in the case of lake ice models, based on projected changes to future climates.

2.5.1 CLIMo

This thesis uses the Canadian Lake Ice Model (CLIMo) to simulate and project historical and future ice conditions of the Tibbitt to Contwotyo Winter Road. CLIMo is a one-dimensional, thermodynamic physical process model used to simulate freshwater ice formation and decay across time (Ménard et al., 2002; Duguay et al., 2003; Morris et al., 2005; Brown and Duguay, 2010; Brown and Duguay, 2012). CLIMo has been extensively validated in various climatological, hydrological, and sensitivity studies, and shown to perform well when the climate state is accurately represented in the input dataset (Brown and Duguay, 2010; 2011) (see Table 2-1).

Table 2-1: Summary of mean bias error results from various CLIMo validation exercises, using data from the Meteorological Service of Canada, at Back Bay, Northwest Territories. The Back Bay station is the closest station to the Tibbitt to Contwoyto Winter Road.

Location	Variable	Mean bias error	Citation
Back Bay, NWT	Ice-on date	5 days	Brown and Duguay (2011)
Back Bay, NWT	Ice-off date	-3 days	Brown and Duguay (2011)
Back Bay, NWT	Ice thickness	0.2 m	Brown and Duguay (2011)
Yellowknife(Back Bay), NWT	Ice-on date	6 days	Ménard et al. (2002)
Yellowknife(Back Bay), NWT	Ice-off date	4 days	Ménard et al. (2002)
Yellowknife(Back Bay), NWT	Ice thickness	0.06 m	Ménard et al. (2002)

Relevant to this study, CLIMo is used to simulate ice phenologies, including ice on (ice-on) and ice off (ice-off) dates, maximum ice thickness, and ice season duration. CLIMo can also be used to simulate ice composition via simulating the presence or absence of an on-ice snow layer, and snow and black ice as a proportion of the total ice layer.

Because lakes in the depth range included in this study and region (1.76 m to 25 m (Macumber et al., 2012; Pienitz et al., 1997)) are typically understood to be isothermal in the ice-off season, CLIMo uses a fixed-depth mixing layer (for the lakes considered in this thesis, considered to be equal to the maximum depth of the lake) to represent the seasonal overturning cycle. During the ice-cover season, the mixing layer is fixed at the surface, and during ice-off periods, the mixing layer is representative of lake size and heat storage capacity as per the energy balance parameterizations. A snow layer can be included in simulations; if present, it is represented as a single layer. When accurate climatological inputs are available, CLIMo has been shown to simulate snowpack properties and phenologies well, as well as its impacts on snow ice formation (Brown and Duguay, 2010; 2011).

CLIMo's surface energy balance calculation can be expressed as:

$$F_o = F_{lw} - \varepsilon\sigma T^4(0,t) + (1-\alpha)(1-I_o)F_{sw} + F_{lat} + F_{sens} \quad (1)$$

where F_o (Wm^{-2}) is the net downward heat flux absorbed at the surface, F_{lw} (Wm^{-2}) is the downward longwave radiative energy flux, ε is the surface emissivity, σ is the Stefan–Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$), T (K) is the temperature, t (s) is the time, α is the surface albedo, I_o is the fraction of shortwave radiation flux that penetrates the surface (a fixed value dependent on snow depth), F_{sw} (Wm^{-2}) is the downward shortwave radiative energy flux, and F_{lat} (Wm^{-2}) and F_{sens} (Wm^{-2}) are the latent and sensible heat fluxes, respectively. CLIMo can be forced with hourly or daily mean values for air temperature (°C), wind speed (m/s), relative humidity (as a percentage), cloud cover, and snow depth (m). For this study, CLIMo was forced with average daily inputs for temperature, humidity, wind speed, cloud cover, and snow cover, for historical conditions replicated by the ERA-Interim atmospheric reanalysis product, and a future climate scenario based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A2, which assumes continually increasing greenhouse gas emissions. (The reader is referred to Duguay et al. (2003) for a detailed description of CLIMo.)

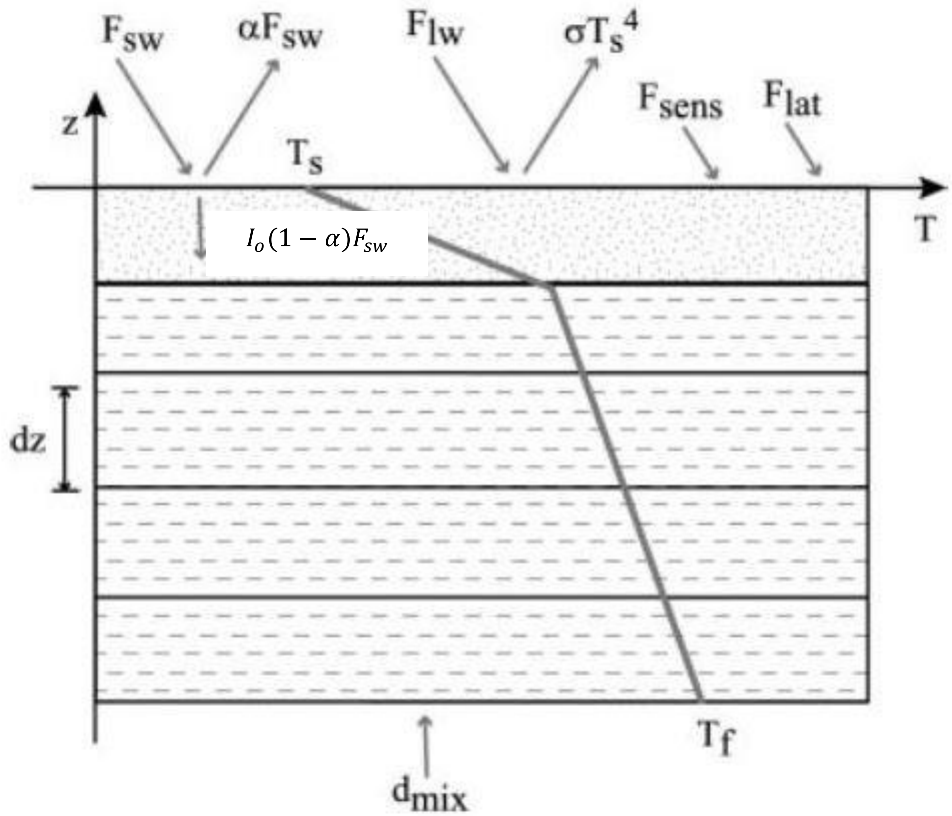


Figure 2-5: Schematic diagram of the Canadian Lake Ice Model (CLIMo) processes during winter. The heavy line represents the temperature profile, the layers with dashes represent ice, and the layer with dots represented snow on the ice surface. (Duguay et al., 2003)

2.6 Input datasets

This section summarizes the datasets used as inputs for CLIMo to simulate historical and project future ice conditions along the Tibbitt to Contwoyto Winter Road. CLIMo requires weather station or gridded climatic data to generate output for ice conditions; two separate rounds of simulations were completed, using different input datasets. First, CLIMo was forced with atmospheric reanalysis data to reproduce historical ice conditions. Reanalysis data is useful for this purpose due to its relatively high accuracy in recreating historical climates, which is especially relevant in northern regions where historical records and weather station data are often limited. Second, CLIMo was run using regional climate model projections to enable projections of future ice conditions, to allow for discussion as to how the ice surfaces might reasonably be expected to change in relation to expected climate changes.

2.6.1 ERA-Interim atmospheric reanalysis data

To facilitate the analysis of historical TCWR conditions (1982-2011), CLIMo was forced with a climate reanalysis dataset. Climate reanalysis is a process by which in situ climatic observations are blended with modeling frameworks and data assimilation schemes to provide a comprehensive, consistent picture of the global climate system across time (NCAR-NCEP, 2013). Reanalyses have the potential to give researchers a single dataset encompassing the entirety of the global climate system, which can act as a highly educated guess at recent historical conditions in the absence of observational data. The immense volume of inputs from around the globe allow reanalyses to be useful for analyzing the recent history of the climate system, when appropriate precautions and an understanding of the limitations of the products are taken into consideration (NCAR-NCEP, 2013).

There are several prominent weather and climate modeling centres which currently produce reputable reanalysis datasets, including the National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the National Aeronautics and Space Administration (NASA). These reanalyses present a strong approximation of the global climate system; however, all global atmospheric reanalysis datasets have been shown to exhibit deficiencies on smaller space and timescales (Decker et al., 2012).

This thesis utilizes the ECMWF reanalysis production, ERA-Interim. The ECMWF has been producing reanalyses since 1979; ERA-Interim is the centre's third reanalysis product, following the completion of the ERA-15 (1979-1993) and ERA-40 (1957-2002) projects. ERA-Interim produces climatic time series from 1979 onwards, and was first described as an 'interim' product to fill space between ERA-40 and the next-generation extended reanalysis product. ERA-Interim continues to be updated forward in time (Dee et al., 2011).

ERA-Interim uses a sequential data assimilation scheme which advances in 12-hourly analysis cycles (Dee et al., 2011). Weather station observations are combined with outputs from the product's internal forecasting model to simulate the state of the global climate on a small time scale, including atmospheric variables (temperature, wind, humidity, and air pressure), surface parameters (2-m temperature and humidity), and precipitation values (Dee et al., 2011). The outputs are then used to provide the prior-state conditions used to simulate conditions at the next timestep.

In a 2012 analysis, Decker et al. compared the ERA-Interim and ERA-40 reanalyses with the NCEP-NCAR Climate Forecast System Reanalysis (CFSR), the Modern-Era Retrospective Analysis for Research and Application (MERRA), and the Global Land Data Assimilation System (GLDAS) products from the NASA Goddard Space Flight Center. The study used flux tower observations to compare various climatological variables, including incoming solar radiation, sensible and latent heat fluxes, precipitation, temperature, and wind speed, for six-hourly, daily, and monthly timesteps. When viewed in comparison with other major reanalysis products, ERA-Interim performs favourably, especially in the high arctic regions which have traditionally been difficult to resolve within traditional modeling frameworks (Decker et al. 2012).

In particular, ERA-Interim shows low root mean square error (RMSE) values for temperature projections. The temperature bias was found to be lowest for ERA-Interim, as well as temperature variability, when compared against other major reanalysis products (ERA-Interim has the most observation locations where the RMSE is less than 1C). ERA-Interim also best captures the winter (December-January-February) diurnal cycle, when measured by lowest RMSE (Decker et al., 2012). Due to its importance in the formation and decay of ice, temperature is an especially important variable to represent accurately for input into an ice modeling framework; however it should be noted that temperature patterns were relatively well-captured by all the major reanalysis products compared to less well-understood climatological variables (Decker et al., 2012).

ERA-Interim also performs well in comparisons of simulated wind speeds, exhibiting the lowest measured RMSE and bias values from among the major datasets (Decker et al., 2012). While ERA-Interim exhibits a positive bias in wind speed projections, the described bias is the lowest of all major products. When comparing precipitation projections, the authors found weaker correlations across all products, with a high degree of variability between study sites. Overall, ERA-Interim was found to over-estimate precipitation values, as did the majority of other products compared, by up to 25 mm day^{-1} depending on the site in question (Decker et al., 2012).

In terms of radiation balance components, ERA-Interim performs very well when comparing the latent heat flux, with correlations exceeding 0.9 for most stations, and is found to best produce monthly variability in the sensible heat flux when compared to other major products. Incoming solar radiation and net radiation are reproduced well across all major products, with ERA-Interim showing high correlations (>0.95) at most stations for incoming radiation, and reproducing net radiation at most stations with a comparably small negative bias of -10-15 Wm^{-2} (Decker et al., 2012).

Decker et al. (2012) also show that ERA-Interim performs better over small timescales (six-hourly and daily) compared to its monthly averages.

2.6.2 Canadian Regional Climate Model data

CLIMo was forced with output from the Canadian Regional Climate Model (CRCM 4.2.0) for a 1961-1990 baseline and a 2041-2070 future scenario. CRCM uses a 45-km grid resolution, and can produce output at up to a 15-minute timestep (Caya and Laprise, 1999). Boundary conditions are provided by the Canadian Centre for Climate Modeling and Analysis (CCCma) General Circulation Model II (GCMII); GCMII also provides macro-scale forcing data to initialize CRCM runs (Caya and Laprise, 1999). CRCM uses the Limited Area Model (LAM) approach, which nests a localized, finer-resolution regional model within a GCM framework, as opposed to Variable Resolution General Circulation Models, which use a finer spatial resolution over the region of study and a coarser spatial resolution over the rest of the globe (Laprise, 2008). CRCM 4.2.0 integrates the Canadian Land Surface Scheme (CLASS) to provide a more realistic representation of the water and energy fluxes between the land and atmospheric components. Regional climate models provide several benefits over the use of general circulation models for work on the regional scale, primarily finer spatial resolution and lower computational costs (Laprise, 2008).

However, problems have been identified with CRCM outputs, most significantly, a temperature bias (Plummer et al., 2006; Gagnon et al., 2009). Plummer et al. (2006) found that

CRCM temperature outputs have a tendency to skew strongly positive (>2C) over much of the continent when the model is forced with CGCM2 data, and strongly negative (>2C) over the arctic regions. When CRCM is forced with atmospheric reanalysis data, Plummer et al. (2006) found that the positive temperature bias over the continent is reduced; however the strong negative temperature bias over the arctic archipelago (-3 to -5C) remains, and must be accounted for when used to force the physical process models used in this thesis. Brown and Duguay (2011) corrected for this bias; more detail is included in the following chapter.

CHAPTER 3: IMPACTS OF HISTORICAL AND PROJECTED CLIMATE CHANGES ON ICE SURFACES OF THE TIBBITT TO CONTWOYTO WINTER ROAD, NORTHWEST TERRITORIES, CANADA

Overview

Seasonal ice roads are a historically important part of the Canadian arctic transportation network. Built over frozen landscapes and water bodies whichu are otherwise unpassable by traditional automobiles, the roads are used to connect remote rural and First Nations communities, as well as industrial projects, in the resource-rich north. One of the most economically significant ice roads runs from Tibbitt to Contwoyto, Northwest Territories, and connects three of Canada's largest diamond mines, with a fourth project in the vicinity set to open in 2017. The road has been constructed annually since 1982 as a joint venture between mine operators Diavik Diamond Mines Inc., BHB Billiton Diamonds Inc., and DeBeers Canada Inc., and requires a minimum ice thickness of 0.7 m to open operations. Recent projections from global climate models suggest an arctic amplification of the global warming signal, as well as changes to arctic precipitation patterns. Projected changes in both air temperature and precipitation have the potential to alter lake ice regimes, with possible economic impacts for the long-term viability of ice roads for moving mine supplies north via land.

This study uses a one-dimensional thermodynamic lake ice model (Canadian Lake Ice Model – CLIMo) to simulate historical ice conditions, and project conditions based on a warmer future climate scenario. CLIMo is first forced with the ERA-Interim reanalysis dataset for the known operations period 1982-2011, with the goal of understanding recent trends in ice season length and ice thickness. CLIMo is also forced with regional climate model output (Canadian Regional Climate Model – CRCM 4.2.0), to make near-future projections of ice-off and ice-on dates and ice thickness. Using road opening and closing dates provided by road managers, we model the historical variability in ice phenologies, as well as project future ice surface conditions. Results suggest marginally later ice-on dates (up to 4 days) and earlier ice-off dates (5 days earlier) for the known historical period, combining for a net reduction in the ice cover season (10 days less), as well as a decrease in maximum ice thickness (up to 0.17 m thinner). A Mann-Kendall trend analysis shows statistically significant trends towards shorter ice seasons

and thinner maximum ice cover for both 3 m and 10 m lake depths (significant at the 0.05 level) . Future projections driven with regional climate model outputs suggest that the trend towards shorter seasons and thinner ice cover will accelerate towards the end of the 21st century, with decreases in season length on the order of three weeks by the 2041-2070 future period, and a net thinning of the maximum ice thickness of up to 0.30 m over the same period.

3.1 Introduction

The Tibbitt to Contwoyto Winter Road (TCWR) is one of Canada's largest and most economically significant ice roads. Ice roads exist over much of the Canadian arctic, and are typically built over frozen lakes, rivers, and permafrost zones. The TCWR is unique for many reasons, including its size (it runs for almost 600 km north from Yellowknife, Northwest Territories); its scope (it costs an estimated $10 million to build annually); its prominent spot in a popular reality TV show, *Ice Road Truckers*; and the fact that it is privately owned, operated, and constructed by the mining companies it serves.

Like much of the Canadian arctic, the Northwest Territories (NWT) are a water-rich landscape, extensively covered by lakes, bogs, marshes, and other categories of surface water. Because of the extreme northern latitude, the landscape is frozen for much of the year. However, the surface water and annual freeze-thaw patterns make building all-season roads a challenge. The TCWR allows seasonal road access to a region which is otherwise impassable by land for the rest of the year. The TCWR makes possible over 5,000 trips every year, to three NWT diamond mines: Snap Lake (DeBeers Canada, Inc.), Diavik (Diavik Canada, Inc.), and Ekati (BHP Billiton). A second DeBeers project, the Gahcho Kué mine, is set to open on route approximately 280 km northeast of Yellowknife by 2017.

The rationale for this study is twofold: first, ice roads are important both economically and socially for communities and resource projects across the Canadian arctic. They are often the only consistent mode of land transportation across the region for months at a time. For land transportation to continue to be consistent, the roads rely on the continued stability of the global cryosphere. Second, the global climate is changing rapidly with significant impacts projected for the cryosphere, including the freshwater ice that ice roads are often built upon. The Canadian arctic has seen significant changes to its cryosphere in the 20th and 21st centuries: arctic surface air temperatures have been observed to be increasing (NOAA Arctic Report Card, 2013); with air temperature changes have come decreases to the snow cover area (NOAA Arctic Report Card, 2013), a shift northward in the continuous permafrost zone (SWIPA, 2011), a decrease in the sea ice minimum observed annually in September (Stroeve et al., 2011), and a shortening of the ice cover season and a decrease in ice thickness for lake and river ice (Brown and Duguay

2011; Duguay 2006). While much effort has been dedicated to understanding how arctic shipping will change in a warmer climate scenario, few studies currently exist that draw connections between climate change and overland transportation methods. While the issue has been recognized by groups that live and work in the region, much of the research remains disconnected, and published internally within companies and groups who stand to be impacted by the changes, published as conference proceedings (MacGregor et al., 2008; Mesher et al., 2008), governmental reports (Andrey et al., 2014) or other 'grey literature', or dealt with in a perfunctory sense in broad reports summarizing changes to the arctic system as a whole (SWIPA, 2011; Warren and Lemmen, 2014). Arctic overland transportation is also useful for study due to the increased attention currently being paid to the Canadian north. Several generations of federal governments have worked to expand Canada's presence in its northern latitudes; as well, economic activity is expected to continue to increase as oil, gas, and other natural resource reserves continue to be uncovered. For economic activity to increase in the region, the capacity to move goods and people safely and efficiently in and out must do the same, and preliminary research suggests that this will become more challenging in a warmer climate.

This study has two closely related objectives: first, by running a lake ice model, the Canadian Lake Ice Model (CLIMo), with ERA-Interim atmospheric reanalysis data, it aims to gain a more comprehensive understanding of historical ice conditions in the region of the Tibbitt to Contwoyto Winter Road (TCWR) for the known operations period 1982-2011 than is currently available given the lack of in situ data available over much of the Canadian north. Second, by forcing CLIMo with Canadian Regional Climate Model (CRCM 4.2.0) outputs for a 2041-2070 future period compared against a 1961-1990 baseline period, it aims to quantify potential changes to lake ice conditions that could impact road operations, such as ice-off and ice-on dates, and maximum ice thickness.

The paper is structured as follows: first, a review of the methods, input datasets, and models used; second, a discussion of the recent historical patterns observed in the ERA-Interim – driven CLIMo results; third, a comparison of the historical results with near-future projections derived from running CLIMo with CRCM inputs; finally, we discuss the results in the context of continued use of the TCWR, and how the season might shift under a warmer climate scenario.

3.2 Methods

3.2.1 Study area

The TCWR runs for almost 600 km from outside Yellowknife, Northwest Territories, to Contwotyo Lake, Nunavut, and has been constructed annually since 1982. It connects in the south to the Ingrahm Trail, the region's northern-most continuous all-weather road. Eighty-seven per cent of its length is built on lake ice, with 64 land portages (Figure 3-1). The average lake depth along the road is estimated to be between 1.76 m (Macumber, 2012; McGregor et al., 2008)) and 8.2 m (Pienitz et al., 1997), and the thickness of naturally-formed ice regularly exceeds 1 m (Tibbitt to Contwoyto Winter Road Joint Venture, n.d.). Previous studies on lakes in the region have identified lake depths between 2.5 m and 25 m, with a median depth of 7 m and a mean depth of 8.2 m (Pienitz et al., 1997). The area isolated for the modeling portion of this project is a box region from 62 to 66N, and 115 to 109W.

The road is built over Taiga Shield and Southern Arctic ecozones. The Taiga shield is an area of discontinuous permafrost, and the Southern Arctic is in the continuous permafrost zone. Because of the underlying frozen layer, the landscape is water-rich with poor drainage, with up to an estimated 30 per cent covered with small, shallow lakes or wetlands (Mackay et al. 2009). This makes building permanent transportation infrastructure a challenge, and most communities and industrial projects in this region are fly-in only, or serviced by road in the extreme winter months. Ice roads (typically defined as being constructed on frozen water) and winter roads (constructed over frozen ground) are the primary or only means of ground transportation throughout much of the Canadian arctic. There are an estimated 5,400 km of ice and winter roads in current annual use across the region (Stephenson et al., 2012).

While many of Canada's seasonal roads are built and maintained by the federal and territorial governments, the study site is a joint private venture built, maintained, and primarily used by the Joint Venture Management Committee (JVMC), a consortium of BHP Billiton Diamonds Inc., Diavik Diamond Mines Inc. and DeBeers Canada Inc, operators of the mines the road services. Today, the road services three diamond mine projects: Snap Lake (Debeers), Diavik, and Ekati (BHP Billiton), with Debeers' Gahcho Kué mine, located 60 km east of its Snap Lake project, set to open in 2017.

Though remote, the site has been popularized by its inclusion in the History Channel reality TV show, *Ice Road Truckers*, which details the unique challenges of transporting materials in such an inaccessible region. The site was selected for use in this study due to its size, history, economic significance, and unique status as privately constructed and operated.

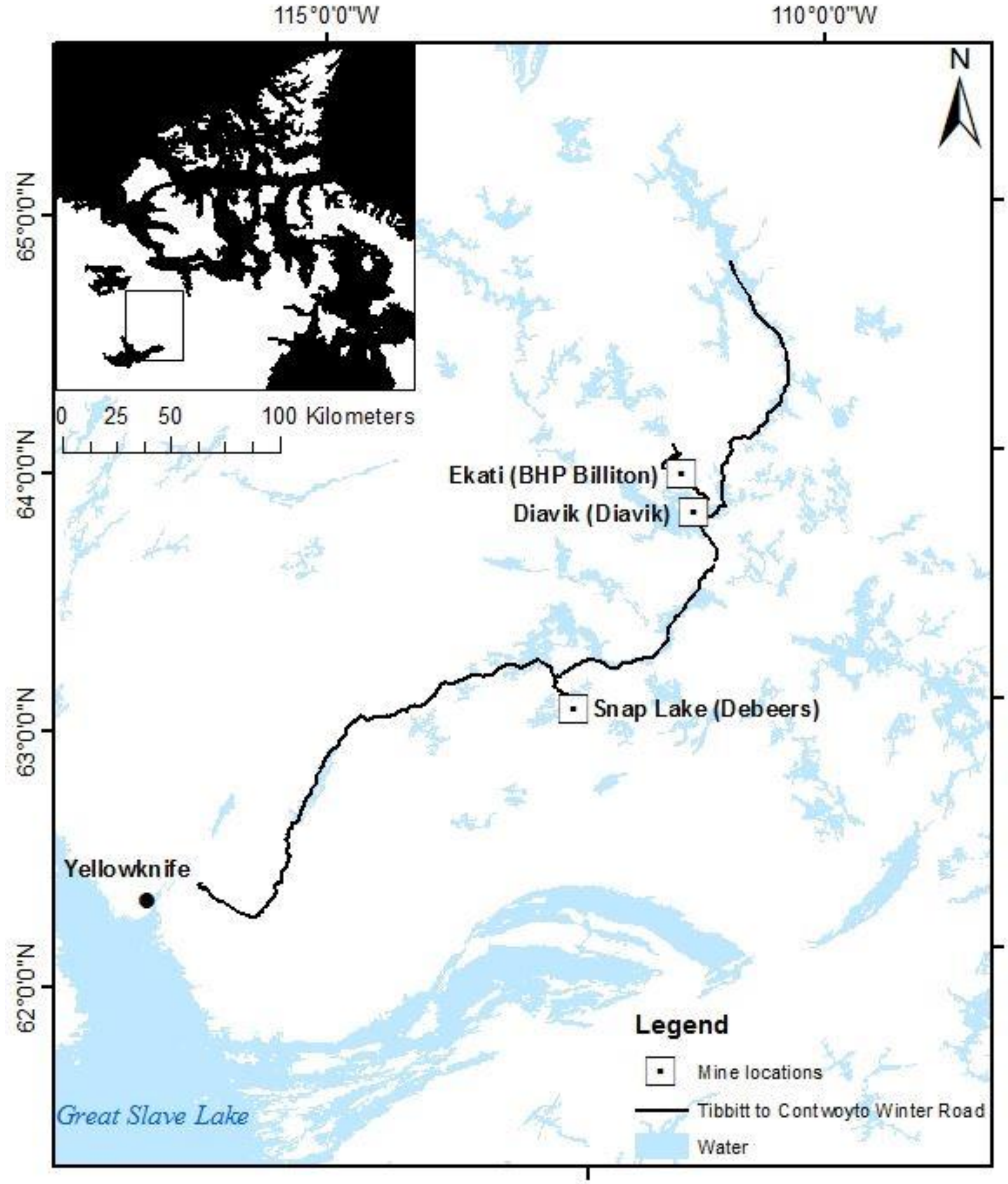


FIGURE 3-1: Map of the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada, showing nearby settlement and mine locations.

3.

This study uses a one-dimensional thermodynamic lake ice model (CLIMo – the Canadian Lake Ice Model) to project changes to ice phenologies within the study site. CLIMo has been used extensively to simulate freshwater ice conditions in the Canadian arctic, including fall ice-on and spring ice-off dates, the progression of ice growth across a winter season, and the composition of the ice surface (black ice or snow ice) (see: Brown & Duguay, 2011; Duguay et al., 2003; Ménard et al., 2002).

CLIMo is adapted from Flato's (1996) landfast sea ice model, and uses Maykut and Untersteiner's (1971) unsteady heat conduction equation:

$$\rho C_p = \frac{\partial T}{\partial t} k \frac{\partial T}{\partial t} + F_{sw} I_o (1 - \alpha) K e^{-kz} \quad (1)$$

where ρ (kg m^{-3}) is density, C_p (J kg $^{-1}$ K^{-1}) is the specific heat capacity, T (K) is temperature, t (s) is time, k (Wm^{-1} K^{-1}) is the thermal conductivity, z (m) is the vertical coordinate (positive downward), F_{sw} (Wm^{-2}) is the fraction of the shortwave radiation flux that penetrates the surface, α is the surface albedo, and K is the bulk extinction coefficient for penetrating shortwave radiation.

From this, CLIMo's surface energy balance calculation can be expressed as:

$$F_o = F_{lw} - \varepsilon \sigma T^4(0, t) + (1 - \alpha)(1 - I_o) F_{sw} + F_{lat} + F_{sens} \quad (2)$$

where where F_o (Wm^{-2}) is the net downward heat flux absorbed at the surface, F_{lw} (Wm^{-2}) is the downward longwave radiative energy flux, ε is the surface emissivity, σ is the Stefan–Boltzmann constant (5.67 × 10-8 $Wm^{-2}K^{-4}$), T (K) is the temperature, t (s) is the time, α is the surface albedo, I_o is the fraction of shortwave radiation flux that penetrates the surface (a fixed value dependent on snow depth), F_{sw} (Wm^{-2}) is the downward shortwave radiative energy flux, and F_{lat} (Wm^{-2}) and F_{sens} (Wm^{-2}) are the latent and sensible heat fluxes, respectively.

For this study, CLIMo was forced with daily inputs for temperature, humidity, wind speed, cloud cover, and snow depth and density (Brown and Derksen, 2013), for the known historical operations period 1982-2011, as well as a future climate scenario based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A2, which assumes continually increasing greenhouse gas emissions.

Because lakes in the depth range included in this study (1.76 m to 25 m (Macumber et al., 2012; Pienitz et al., 1997)) and region are typically understood to be isothermal in the ice-off season, CLIMo uses a fixed-depth mixing layer (considered to be equal to the maximum depth of the lake) to represent the seasonal overturning cycle. During the ice-cover season, the mixing layer is fixed at the surface, and during ice-off periods, the mixing layer is representative of lake size and heat storage capacity as per the energy balance parameterizations. When snow is present on the ice, it is represented as a single layer. When snow is present on the ice in sufficient quantities, CLIMo will simulate snow ice formation via the depression and flooding of the ice surface; the added mass of the refrozen water in the snow pores is added to the total ice thickness outputs as snow or 'white' ice. CLIMo has been shown to simulate the on-ice snowpack well compared to observations, when provided realistic input data (Brown and Duguay, 2011).

3.2.3 Model inputs

ERA-Interim

In the absence of comprehensive, consistent historical meteorological station data, CLIMo is first forced with the European Center for Medium-Range Weather Forecasts' (ECMWF) ERA-Interim reanalysis dataset. ERA-Interim features finer spatial resolution (0.75 deg.) when compared to ECMWF's previous reanalysis product, ERA-40, and has been shown to perform well at reproducing atmospheric patterns and phenomena when compared against other current reanalysis products, especially in the traditionally hard-to-resolve arctic regions (Decker et al., 2012).

ERA-Interim uses a 12-hour timestep, 0.75-degree grid cell resolution, with 60 vertical levels in the atmosphere (Dee et al., 2011). While all reanalysis products falter on smaller spatial scales, Decker et al. (2012) showed that ERA-Interim exhibits relatively low biases across most fields of computation. Of particular relevance for the simulations performed in this study, ERA-Interim has been shown to be effective when simulating surface air temperatures, especially the winter (December through February) diurnal cycle. As well, ERA-Interim is shown to perform the best out of the products surveyed for 6-hour wind speed projections, with both the lowest observed bias and standard deviation of errors. The final field used for CLIMo computations is snow accumulation; ERA-Interim exhibits moderate biases for both monthly and 6-hourly analyses, but shows a relatively low standard deviation of errors compared to the other products. Though not used as inputs for CLIMo, in terms of radiation balance components, ERA-Interim performs very well when comparing the latent heat flux, with correlations exceeding 0.9 for most stations, and is found to best produce monthly variability in the sensible heat flux when compared to other major products. Incoming solar radiation and net radiation are reproduced well across all major products, with ERA-Interim showing high correlations (>0.95) at most stations for incoming radiation, and reproducing net radiation at most stations with a comparably small negative bias of -10 to -15 Wm^{-2} (Decker et al., 2012). Relevant to the input requirements of CLIMo, Decker et al. (2012) also show that ERA-Interim performs better over small timescales (six-hourly and daily) compared to its monthly averages; daily averages values were used as inputs into CLIMo.

CRCM

To enable future projections, CLIMo was forced with Canadian Regional Climate Model output (CRCM 4.2.0). CRCM is limited in area, and uses the Canadian Land Surface Scheme (CLASS) to describe land–atmosphere water and energy exchanges. One CRCM scenario is used for this study, based on the Intergovernmental Panel for Climate Change A2 emissions scenario (continually increasing carbon dioxide emissions). For a full description of the CRCM, see Laprise (2008).

CRCM uses a 45-km grid resolution (true at 60N), and can produce output at up to a 15-minute timestep (Caya and Laprise, 1999). Boundary conditions are provided by the Canadian Centre for Climate Modeling and Analysis (CCCma) General Circulation Model II (GCMII); GCMII also provides macro-scale forcing data to initialize CRCM runs (Caya and Laprise, 1999). CRCM uses the Limited Area Model (LAM) approach, which nests a localized, finer-resolution regional model within a GCM framework, as opposed to Variable Resolution General Circulation Models, which use a finer spatial resolution over the region of study and a coarser spatial resolution over the rest of the globe (Laprise, 2008). CRCM 4.2.0 integrates the Canadian Land Surface Scheme (CLASS) to provide a more realistic representation of the water and energy fluxes between the land and atmospheric components. Regional climate models provide several benefits over the use of general circulation models for work on the regional scale, primarily finer spatial resolution and lower computational costs (Laprise, 2008).

A cold bias has been identified previously in CRCM data across the arctic (Plummer et al., 2006; Gagnon et al., 2009). The bias was corroborated by author comparisons indicating that CRCM temperature simulations for the study area were up to one degree Celsius colder than Environment Canada observations taken from the Back Bay meteorological station, near Yellowknife, NWT. CLIMo has been shown to be sensitive to temperature variability on the order of 1C (Ménard et al., 2002). To compensate, a bias correction was applied for the temperature inputs using Environment Canada weather and climate records taken from 47 stations across the Canadian arctic (Brown and Duguay, 2011). The mean monthly bias was calculated from the 1961-1990 projections; the bias was assumed to continue in the immediate future, and the bias correction was continued through the end of model runs in 2100.

3.2.4 Model simulations and outputs

CLIMo can produce output for ice phenologies (ice-on and ice-off dates, from which ice season duration can be calculated), and ice thickness on a daily, for lakes at any specified depth. Additionally, CLIMo can simulate ice growth in either the presence or absence of input dataset-dictated snow cover. The option to remove modeled snow cover is important in this context because it mirrors a basic engineering technique used in TCWR construction, where engineers remove snow cover to expose the ice surface to cold surface air masses, allowing it to thicken more quickly.

Results were filtered to apply to the physical constraints of the study area. Simulations were run for theoretical lakes within the study area with depths of 3 m (representative of the majority of lakes along the road route), and 10 m (estimated to be representative of the maximum depth of lakes the road passes over) (Macumber et al., 2012; Pienitz et al., 1997). Results were also computed with and without snow cover to attempt to compare road engineers' attempts to thicken the ice surface by removing snow along the route.

CLIMo is first forced with ERA-Interim data, for the known operations period 1982-2011. Results were averaged to give daily values for ice thickness and composition. From this, ice-on and ice-off dates, ice season duration, and maximum annual thickness were determined. Four sets of ice surface simulations were produced: for 3 m deep lakes, with and without simulated snow cover, and 10-m deep lakes, with and without snow cover. Anomalously short and long ice seasons were identified, to aid discussion of the impacts of anomalously warm and cool years on ice season operations.

A Mann-Kendall trend analysis was performed to determine the significance of trends for ice-on and ice-off dates, ice cover duration, and maximum ice thickness, for 3-m and 10-m deep lakes with and without simulated snow cover. The Mann-Kendall test is a non-parametric trend analysis tool commonly used to analyze environmental datasets. The test determines whether data as a time series shows a positive or negative trend, given a predetermined significance level. The analysis was paired with the Sen's Slope method to quantify the rates of change in the selected variables between 1982 and 2011.

Finally, CLIMo was run with CRCM input data for the period 1961 to 2100. Model outputs were combined into 30-year mean periods: a 1961-1990 baseline period, compared against 2041-2070 future scenario. The baseline corresponds with the commencement of operations in 1982, and 2041-2070 corresponds roughly to end-of-operations estimates. CLIMo was again run four times (for 3-m and 10-m lakes with and without snow cover,). The same four variables were selected as especially relevant to the study of changing ice road conditions (ice-on dates, ice-off dates, total ice season duration, and maximum ice thickness) and the difference between the 2041-2070 and 1961-1990 baseline was calculated for broader comparison, and to aid discussion of the future of the TCWR in a warmer climate.

3.3 Results

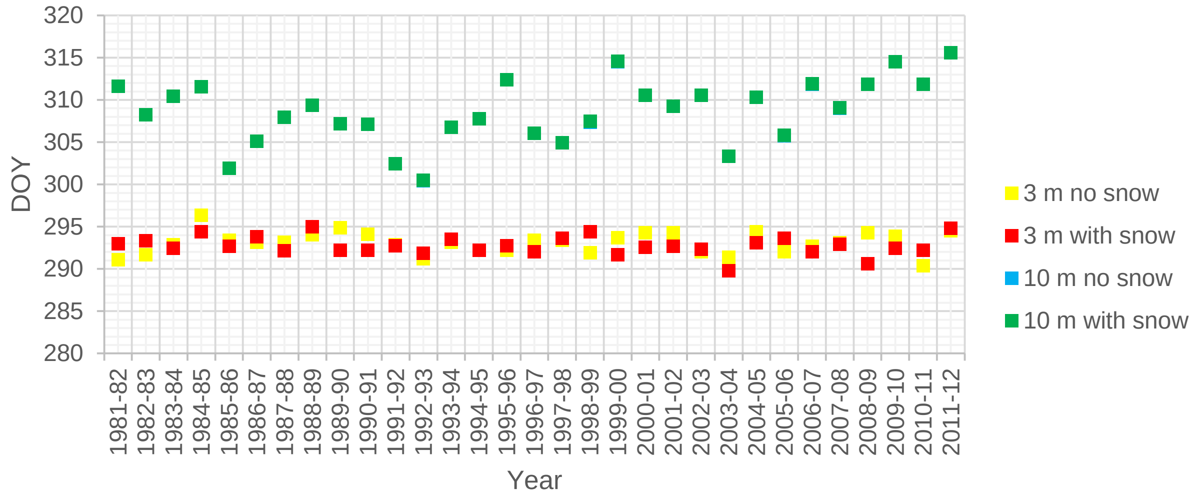
3.3.1 Historical trends

Ice-on and ice-off dates

Simulations using ERA-Interim reanalysis data show ice-on dates to be similar for 3 m lakes, regardless of the snow scenario, and for 10 m lakes, regardless of simulated snow cover (Figure 3-2). The simulations also show larger ice-on anomalies for the 10 m lakes than for 3 m lakes – the average absolute anomaly for the 3 m lakes is one day, versus three days for the 10 m lakes (Table 3-1). When a Mann-Kendall trend analysis is performed, no consistent change in ice-on dates is observed. None of the trends are statistically significant; however, the high degree of variability observed, especially for the 10 m lakes, suggests that temperature and lake depth are significant controls on the potential road season, via their influence on ice growth and decay, as well as suggesting that climate variability, as well as trends, pose a challenge for operations planning purposes. Also, the results indicate that shallow lake processes are driven more so by local weather conditions, versus deeper lakes which are primarily driven by longer weather patterns or seasonal climate due to a longer climate 'memory', or the larger heat storage potential of the water to store energy from earlier in the season or year. Finally, the lesser degree of variability observed in the 3 m lakes, with ice-on occurring almost uniformly in the middle of October for the duration of the 1982-2011 study period indicates that early fall temperatures may be relatively stable from year to year, whereas the relatively greater variability in ice-on dates for the 10 m lakes, occurring between late October and middle of November, suggest that shoulder season temperatures may be less consistent as well. This is corroborated by Mesher et al. (2008) who identify November and April as the most variable sections of the operations season.

TABLE 3-1: Changes to ice-on and ice-off dates, ice cover duration, and mean maximum ice thickness between 1982-2011, when forced with ERA-Interim reanalysis data (*results significant at 0.05 level). Positive values indicate a shift earlier in the calendar year, and negative values indicate a shift later in the calendar year.

Variable	**Scenario**			
	3m		**10m**	
	0 snow	**100 snow**	**0 snow**	**100 snow**
Ice-on (days later)	0.2	-1.0	3.9	3.9
Ice-off (days earlier)	-2.9	0.9	-4.7	-5.3
Ice cover duration (days less)	-2.9	2.0	-9.8*	-9.5*
Mean maximum thickness (decrease in m)	-11.4	-14.7*	-12.3	-17.1*



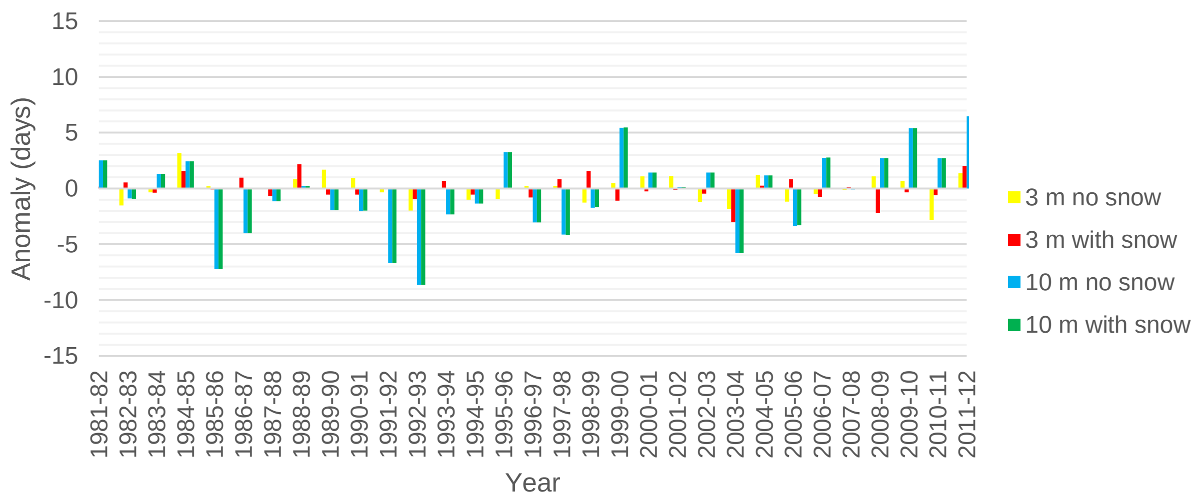
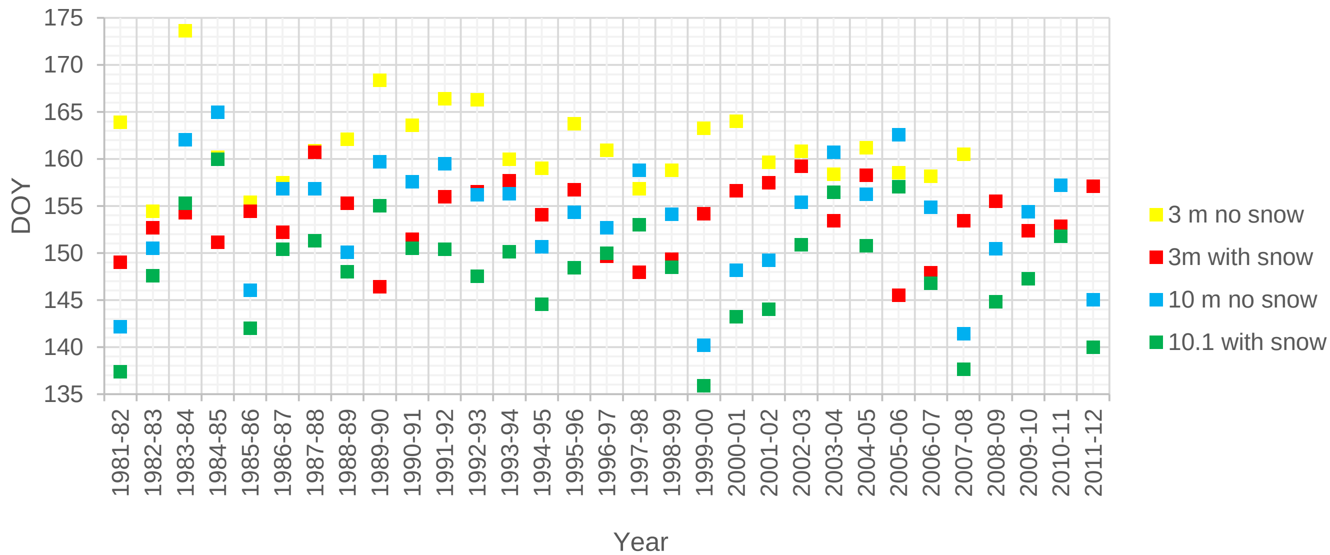


FIGURE 3-2: Time series of CLIMo-ERA-Interim simulations for ice-on dates, and ice-on anomalies averaged for the entire study area for the 1982-2011 period.

Simulated ice-off dates are more variable across both depth and snow scenarios (Figure 3-3); this can possibly be explained by the understanding that ice-off events are largely driven by a single climatic variable — in this case, surface air temperatures (Bonsal et al., 2006) — as opposed to ice-on events which are also controlled by the heat storage potential of the water as determined by lake depth. Aside from air surface temperatures, ice-off events are also related to ice thickness and snow cover at the onset of melt; holding surface air temperatures constant, it would take longer to melt a thicker ice surface and snow layer, therefore making the date of ice-off later in the year. A Mann-Kendall trend analysis finds earlier ice-off dates on the order of 0.9 days later in the year to 5.3 days earlier in the year from 1982 to 2011, depending on snow cover and lake depth. None of the trends are found to be statistically significant (Table 3-1).



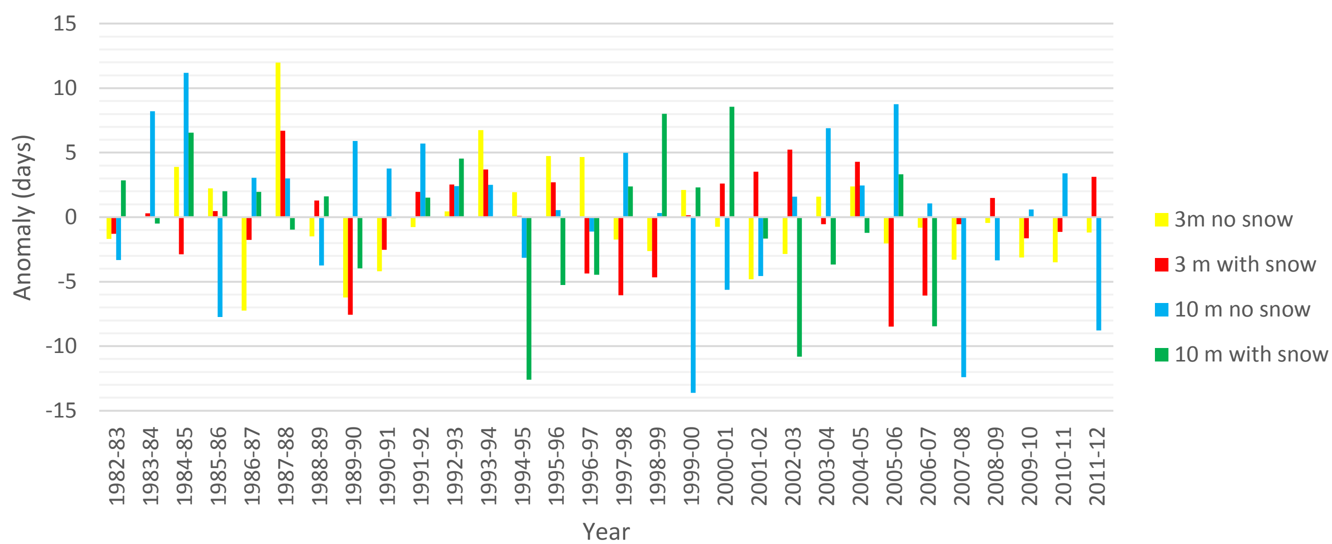
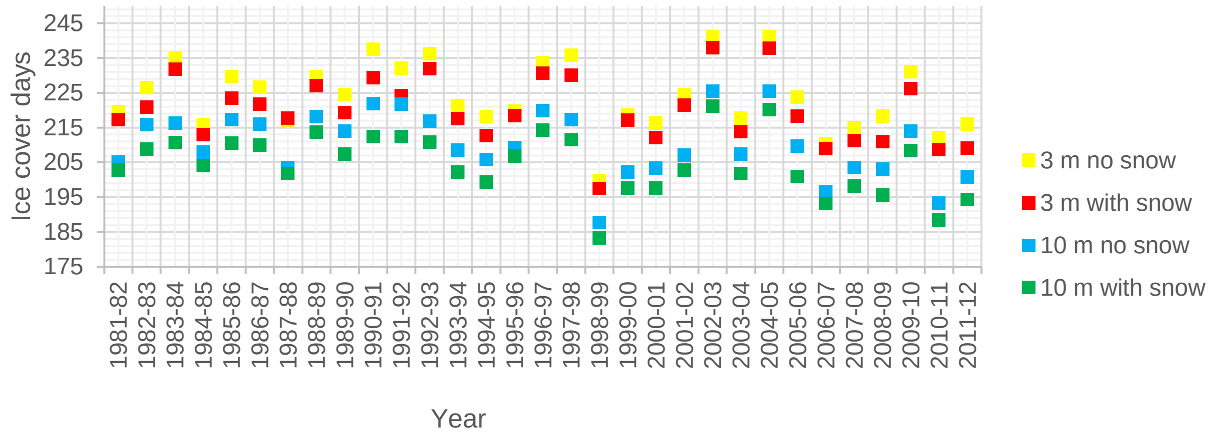


FIGURE 3-3: Time series of CLIMo-ERA-Interim projections for ice off dates and anomalies for the 1982-2011 period.

Ice cover duration

The simulated later ice-on dates and earlier ice-off events combine for a net decrease in the ice cover season across all lake depths and snow scenarios between 1982 and 2011 (see Table 3-1). The trend towards shorter ice cover seasons is consistent across all model runs, with ice surfaces for all runs reacting similarly to warm and cool year temperature inputs, such as the 1998 known strong El Nino year (Corti et al., 1999; Moritz et al., 2002), and in 2006-2007 winter (Figure 3-4), corresponding with the low sea ice minimum observed in 2007. While the magnitude of the ice responses differs based on lake depth and snow scenarios, the anomalies for all model runs almost always shift positive or negative together. The Mann-Kendall test shows trends towards shorter ice cover seasons over the 1982-2011 period for all depth and snow scenarios: a net decrease of -2.9 days for 3 m lakes with no snow cover; an increase of 2.0 days for 3 m lakes with simulated snow cover; and decreases of 9.8 and 9.5 days for 10 m lakes without and with snow cover present on the ice surface, respectively (see Table 3-1). The results for 10 m lakes with and without snow were found to be statistically significant at the 0.05 level.



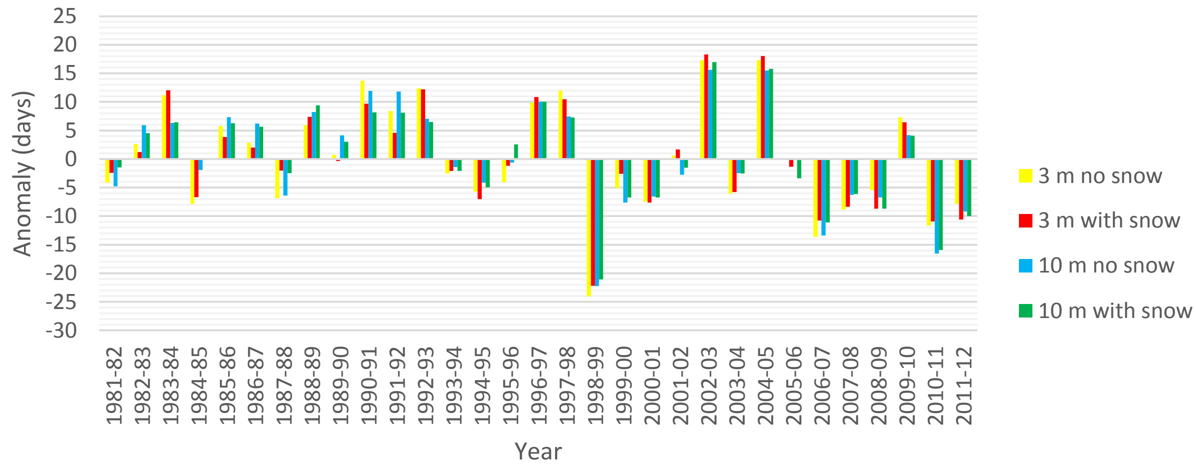
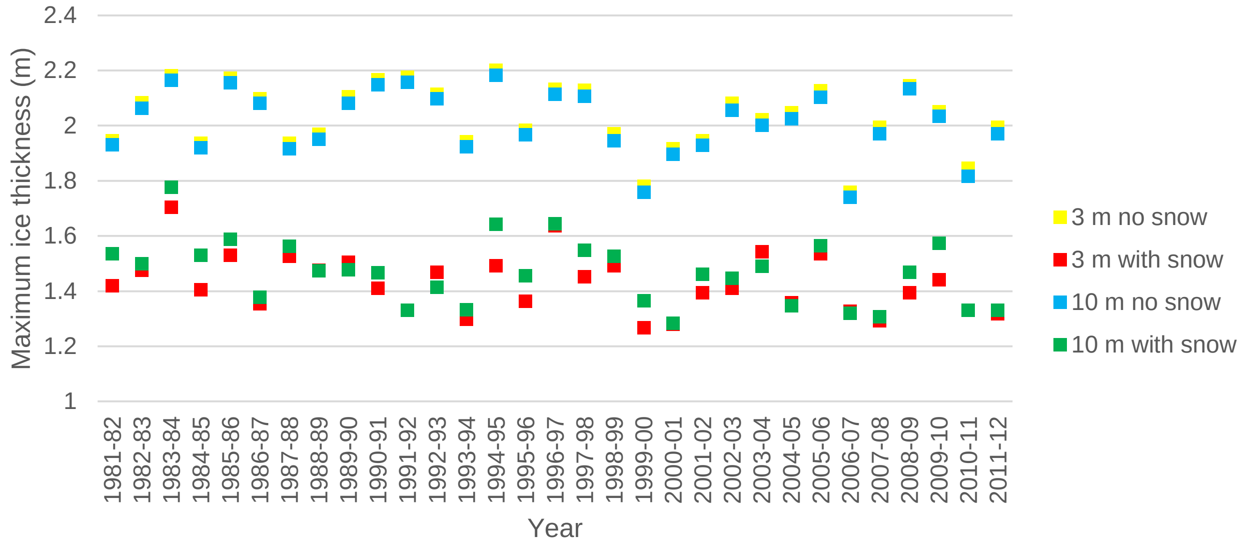


FIGURE 3-4: Time series of CLIMo-ERA-Interim projections for ice season duration and anomalies for the 1982-2011 period.

Maximum ice thickness

Modeled simulations for maximum ice thickness for all snow and lake depth scenarios exhibit marked decreases over the 1982-2011 period. Lake ice thickness is predominantly precipitation (i.e. snow) controlled; this is observed in the historical simulations. Three and 10 m lakes with no simulated snow cover react similarly, showing a decrease in thickness of 0.11 m and 0.12 m, respectively, while 3 m and 10 m lakes with simulated snow cover show a simulated decrease in maximum thickness of 0.15 m and 0.17 m, respectively (see Table 1). The decreases in thickness for 3 m and 10 m lakes with simulated snow cover are found to be statistically significant at the 0.05 level.



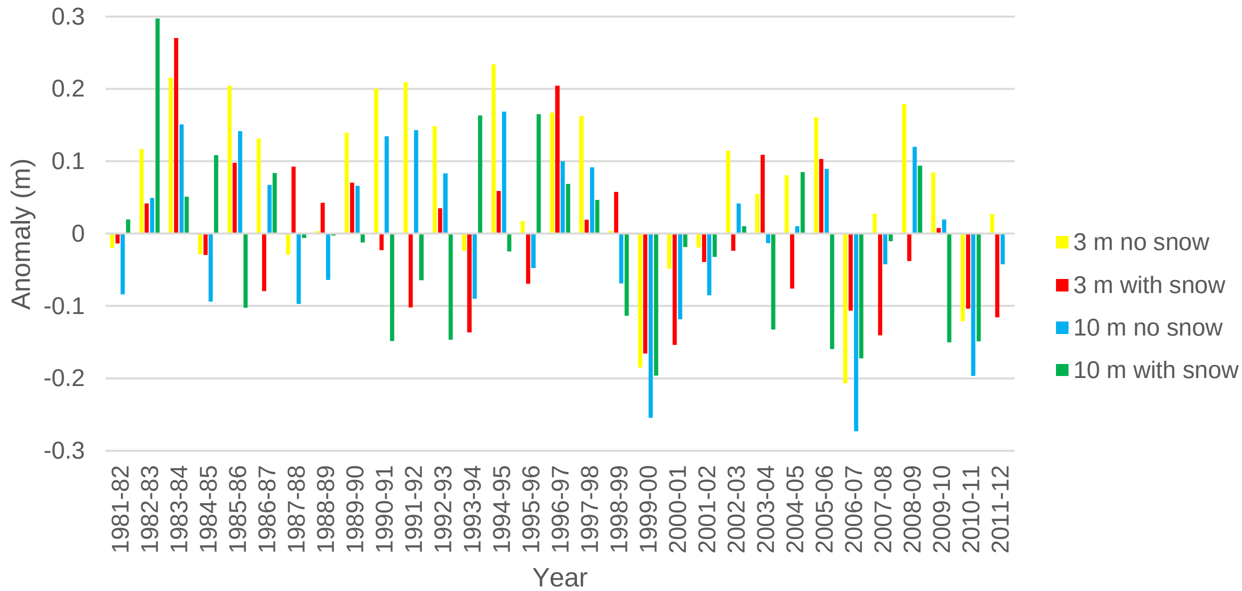


FIGURE 3-5: Time series of CLIMo-ERA-Interim projections for mean maximum ice thickness and thickness anomalies for the 1982-2011 period.

3.3.2 Projected

Ice-on and ice-off dates

For 3 m lakes, CLIMo projects delays of ice-on of 4-11 days across the study area between the 1961-1990 baseline and 2041-2070 comparison period. The projected delay in ice-on dates for 10 m lakes is 5-8 days across the region. On the 3 m lakes, lakes at southern latitudes are projected to see the greatest delay in ice-on (8 days), while more northern lakes will be delayed by 4-6 days. However, this pattern is reversed with the 10 m lakes, where results show that southern lakes will see freeze-up delayed by 4-5 days, while northern lakes will see it delayed by up to 6 days. (Table 3-2.)

TABLE 3-2: CLIMo projections for changes to ice-on dates, ice-off dates, ice cover duration, and mean maximum ice thickness between 1961-1990 and 2040-2070

Variable	**Scenario**			
	3m		**10m**	
	0 snow	**100 snow**	**0 snow**	**100 snow**
Freeze-over (days later)	4-10	4-11	4-8	4-8
Break-up (days earlier)	8-14	5-11	8-14	7-11
Ice cover duration (days less)	15-24	12-22	14-23	13-20
Mean maximum thickness (decrease in m)	0.27-0.30	0.15-0.21	0.28-0.30	0.17-0.29

Projected ice-off dates suggest that ice-off is more strongly influenced by snow and its insulating properties, than by lake depth. This is corroborated by the work of Bonsal et al. (2006), who argue that the timing of ice-off can be predicted by the movement of the zero-degree isotherm.

In simulations where snow is not present on the ice surface, 3 m and 10 m lakes are projected to see ice-off events occurring up between 8-14 days earlier across the study region by 2041-2070; for lakes with simulated snow cover, ice-off is projected to occur between 5-12 days earlier (Figure 3-7). Across all simulations, southern lakes are projected to see more moderate changes (5-10 day), while northern lakes will see the most extreme shift towards earlier ice-off events (8-11 days).

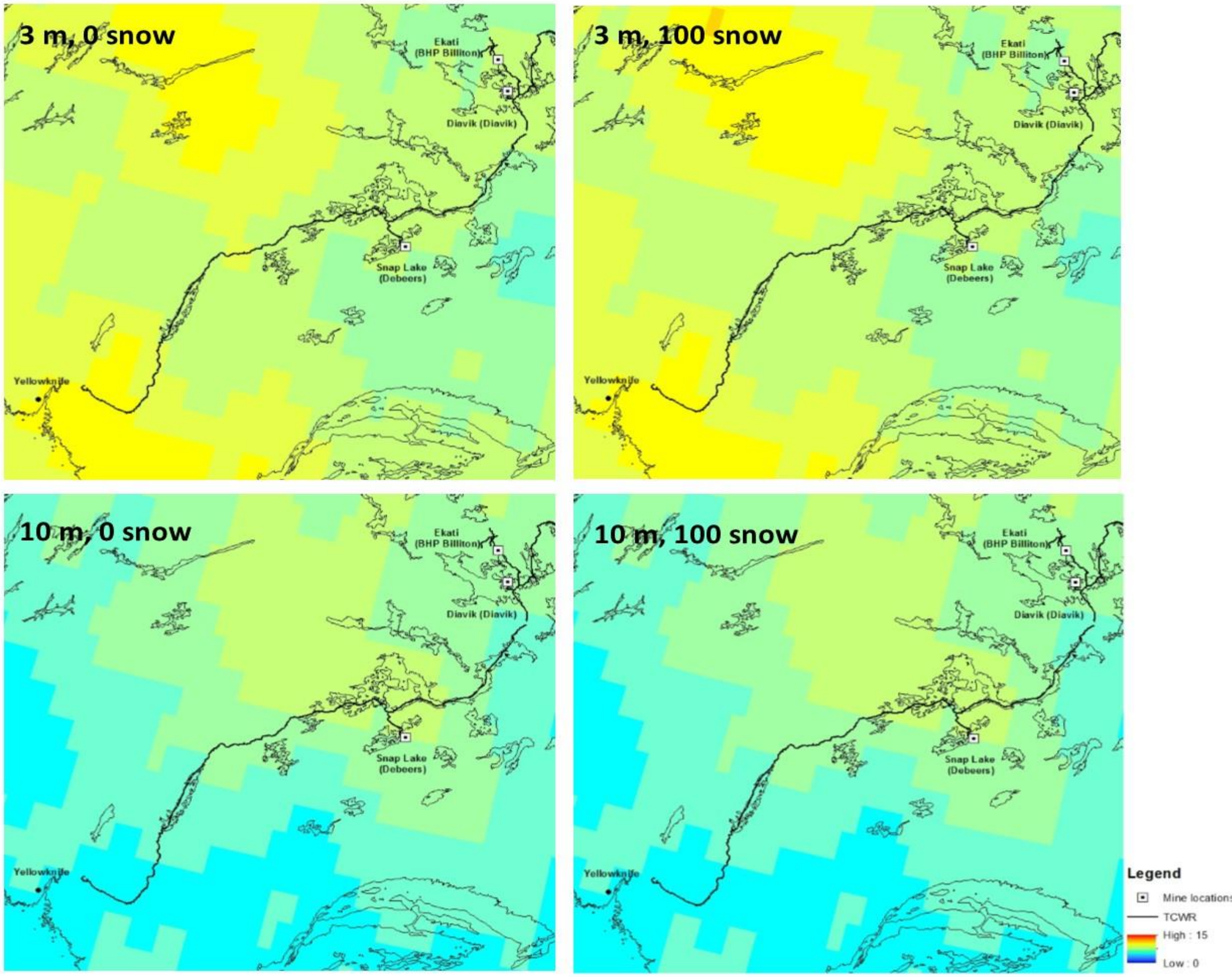


FIGURE 3-6: CLIMo-CRCM projections for changes to ice-on dates (in days later in the calendar year), as the difference between the 1961-1990 baseline and the 2041-2070 future period. '100 snow' indicates full simulated snow cover; '0 snow' indicates snow cover was removed for the simulations.

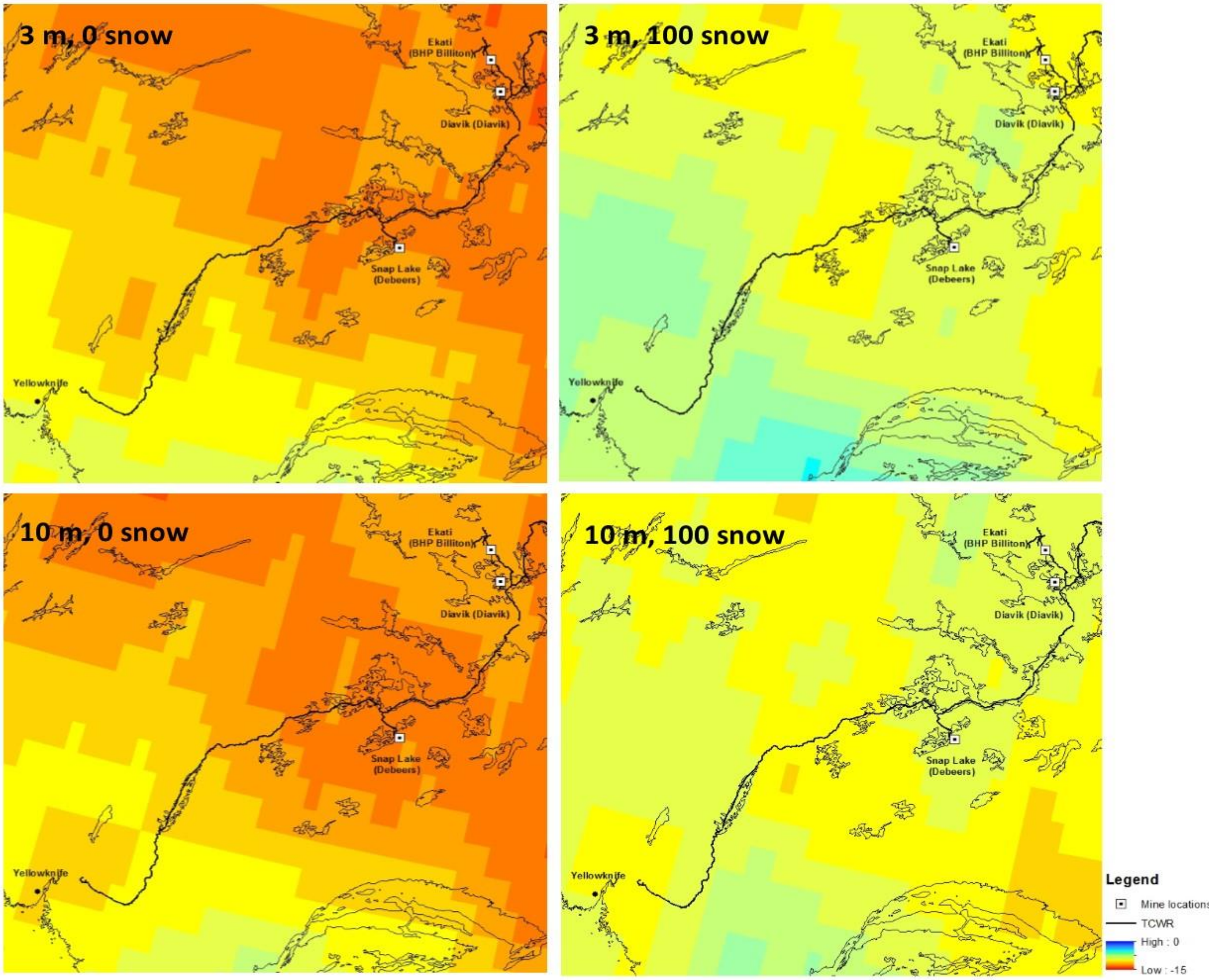


FIGURE 3-7: CLIMo-CRCM projections for changes to ice-off dates (in days earlier in the year), as the difference between the 1961-1990 baseline and the 2041-2070 future period.

Ice season duration

Ice cover season duration was calculated by combining projections for ice-off and ice-on events; as such there are more pronounced spatial patterns across varying lake depths and snow scenarios. Simulations run for 3 m lakes with snow present on the ice are projected to see a net season shortening of 5-22 days, and 10 lakes with modeled snow cover are projected to experience seasons shorter by 13-20 days by 2041-2070 (Figure 3-8). When snow cover is removed from the simulations, 3 m lakes are projected to see a decrease in season duration on the order of 17-25 days. 10 m deep lakes without simulated snow are projected to lose between 14-22 ice cover days by 2041-2070.

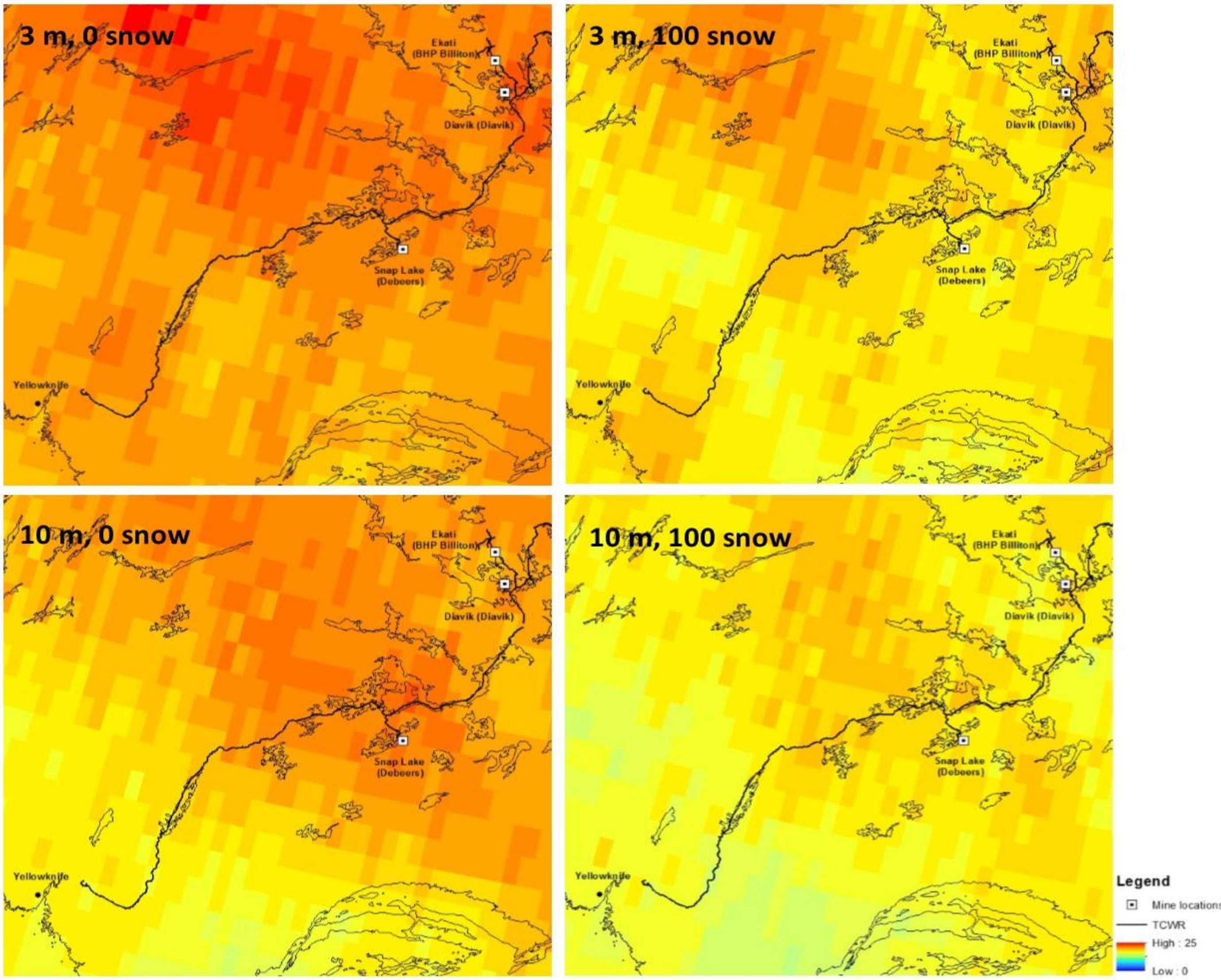


FIGURE 3-8: CLIMo-CRCM projections for changes to ice season length (in days), as the difference between the 1961-1990 baseline and the 2041-2070 future period.

Mean maximum ice thickness

CLIMo projections for changes to mean maximum ice thickness show a strong divide between scenarios with and without snow cover, demonstrating the importance of snow as an insulator for ice surfaces (see Ménard et al, 2002; Duguay et al, 2003, among others). For 3 m lakes with a snow layer simulated, mean maximum ice thickness is projected to decrease by 0.15-0.31 m, and for 10 m lakes, the projected decrease is 0.17-0.29 m across the study area (Figure 3-9). However, simulations without snow cover see relatively homogeneous results across the study area and irrespective of lake depth, at 0.27-0.30 m. There are no strong spatial trends visually apparent.

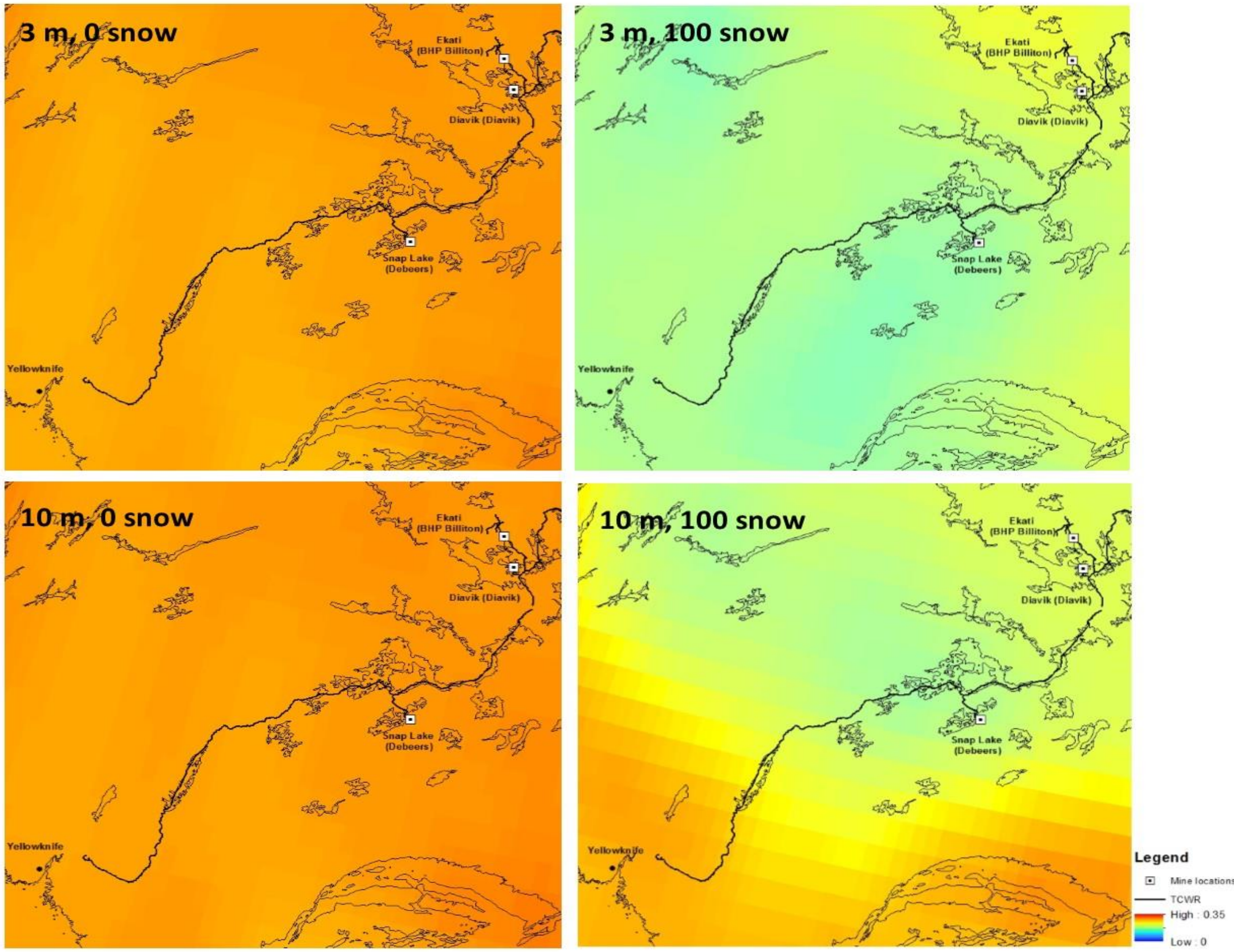


FIGURE 3-9: CLIMo-CRCM projections for changes to mean maximum ice thickness (in metres), as the difference between the 1961-1990 baseline and the 2041-2070 future period.

3.4 Discussion

3.4.1 Historical

Changes to ice-on and ice-off dates, ice season duration, and maximum ice thickness

When CLIMo is forced with ERA-Interim atmospheric reanalysis data, results show that changes to ice-off dates contribute more to the overall season shortening than do changes to ice-on dates. The anomalies for ice-off dates are also found to be greater than the anomalies for ice-on dates. This is likely because ice-off is largely a function of a single climatic variable (surface air temperatures and the timing of the movement of the 0C isotherm), assuming constant snow and ice thickness at the onset of melt, while ice-on dates are determined not only by immediate surface air temperature change, but also by stored energy in the water. As such, ice-on dates are related closely to lake depth, as well as temperature earlier in the year (e.g. an exceptionally warm summer may result in an increase in stored energy, translating to later ice-on events).

Some ice phenology indicators respond more uniformly to climatic changes than others; for example, ice-on and ice-off dates exhibit relatively 'noisy' responses, with scenarios responding in line with snow cover or lake depth, but showing positive and negative anomalies often in the same year, depending on the model run. All scenarios for ice cover duration, however, respond relatively coherently (i.e. all four scenarios responding with positive or negative anomalies for the same year).

Maximum ice thickness is both temperature and precipitation-driven; this is reflected in the ERA-Interim-forced CLIMo simulations, where a time series of ice thickness change over the 1982-2011 period shows clear relationships between lakes of different depths but under the same snow cover scenarios, where greater decreases in thickness are observed in model runs where snow is present on the ice (Figure 3-5).

The rate of change, while statistically significant for 3 m lakes with snow cover and 10 m lakes with snow cover (at the 0.05 level) is still relatively moderate, and on its own does not seem likely to reduce the utility of the TCWR by the ice never reaching the 0.7 m threshold to commence operations.

Ice cover changes and relationship to known road seasons and events

This study discusses road open and close dates as being analogous to when the ice surface exceeds 0.7 m in thickness. The 0.7 m threshold is suggested by road managers (Mesher et al., 2008) and is a useful guideline. However, in reality other factors come into play when determining opening and closing dates, including adverse weather conditions, or structural concerns on the ice surface, such as dynamically formed cracks or holes (Tibbitt to Contwoyto Winter Road Joint Venture, n.d.). In particular, using the 0.7 m threshold for determining road closing dates may be problematic due to the high degree of uncertainty surrounding road closing protocols, for example due to ice-off processes such the formation of ice candles, or columns of ice running perpendicular to the surface. This formation allows water to percolate through the ice layer; the infiltration of water, sediment, or air through the ice layer causes internal melting, and a decrease in the structural integrity of the ice sheet, though the ice sheet may still be thick while the candling is occurring (Ashton, 1985).

As well, it is important to note that road conditions are not a perfect proxy for climatic changes in the region. While lake and river ice conditions are traditionally understood as good proxies for climatic change due to their high sensitivity to changes, the lake ice of the TCWR is heavily engineered to ensure the safety of drivers and operators. Common techniques include removing surface snow and exposing the ice to the cold overlying air masses, and flooding the exposed surfaces to facilitate ice growth from both above and below; these efforts would 'smooth' any in situ ice growth data. This has the effect of making ice road surfaces more resilient to climate changes than they would be naturally, benefiting road operators.

However, while the TCWR is heavily engineered, temporarily decreasing the influence of climatic changes on the ice surfaces, it is likely that due to size, scale, or budgetary concerns, other roads across the Canadian arctic are not altered to the same degree, if at all. In these cases, CLIMo or other purely physical ice process models may see more success at predicting climate-driven changes to the ice or ice road seasons. The TCWR is unique among Canadian ice roads due to its size and the fact that it is privately constructed, owned, and operated by the Joint Venture Management Committee (JVMC), made up of representatives from BHP Billiton

Diamonds Inc., Diavik Diamond Mines Inc., and DeBeers Canada Inc. The financial and intellectual resources available to this project likely far exceed those available to smaller government-run projects serving less lucrative projects or communities.

When looking at trends instead of variability, the Mann-Kendall and Sen's Slope analyses used 30 years of data, with each year comprised of the average of 36 grid cell outputs. The quantity of data lends confidence to the results, and make the analyses useful tools for quantifying rates of change across climate variables for the purposes of ice road season analysis that have only been implied until this point. However, while statistical significance is important measure from a scientific standpoint, and is a good threshold from a decision-making or operational standpoint as well, the lack of uniform statistical significance across all indicators should not be interpreted to mean that no change in the climate conditions or the ice surfaces has occurred or is occurring. A multitude of evidence exists supporting the changes in surface air temperatures and precipitation patterns in arctic regions (NOAA Arctic Report Card, 2013), as well as changes to arctic freshwater ice cover (Duguay, 2006; Bonsal et al., 2006; Brown and Duguay, 2010; Brown and Duguay, 2011).

Another benefit of reconstructing historical ice conditions is it allows comparisons of anomalously long and short ice seasons with known climatic conditions during those seasons. For example, 1998 was a strong El Niño year (Corti et al., 1999; Moritz et al., 2002); the 1998-1999 ice cover season in the TCWR region responded with decreases in ice cover days across all snow and depth scenarios on the order of 21 to 24 days. Mean maximum thickness for the season also showed marked decreases, on the order of 0.15 m for 3 m lakes with no simulated snow cover, and 0.24 m for 10 m lakes with no snow cover.

The connections between anomalously short ice seasons and shipping capacity is less clear, however. When looking at historical road records, total tonnage shipped does not necessarily correspond to the number of trips made along the road (see Table 3-3 for a road open and close dates, and basic shipment info made available by the Tibbitt to Contwoyto Winter Road Joint Venture on their website, for 2002-2012), and neither indicator of a 'successful' ice road season necessarily correlates to number of days the road was open. For example, the 2005-2006 season was cut short due to poor ice conditions, necessitating over 1200 loads having to be flown into the mines over the summer season, at great cost to the companies (Mesher et al, 2008). However, while the model results reflect the climatic anomalies of the 2005-2006 season, shorter ice road seasons are also observed, for example in 2009-2010, in which road operators report the road was open for only 44 days, with the fewest trips recorded and the lowest tonnage moved (Tibbitt to Contwoyto Winter Road Joint Venture, n.d.). There is no public record of an unusually high number of fly-in trips made in the off-season to compensate for the short road season. Road managers were contacted and unable or unwilling to comment on the specific differences between the observed climatic and/or operational conditions of the two seasons.

TABLE 3-3: Road open and closing dates, as provided by the Tibbitt to Contwoyto Winter Road Joint Venture website (www.jvTCWR.com) and Mesher et al. (2008), as well as total northward trips and tonnes hauled.

Year	Road open (DOY)	CLIMo-projected road open (ice >0.7m)	Road close (DOY)	Season length (days)	Tonnes	Trips
2001-2002	26	21	117	91	256,915	7,735
2002-2003	32	17	92	60	198,818	5,243
2003-2004	28	20	90	62	179,144	5,091
2004-2005	26	8	96	70	252,533	7,607
2005-2006	37	32	87	50	177,674	6,841
2006-2007	27	20	100	73	330,002	10,922
2007-2008	29	16	90	61	245,585	7,484
2008-2009	32	8	81	49	173,195	4,847
2009-2010	36	14	80	44	120,020	3,508
2010-2011	28	16	90	62	239,000	6,832

3.4.2 Projected

Changes in ice-off, ice-on, and ice season duration

When considering the future viability of ice roads for heavy haul transportation, there are two primary factors for study: changes to ice presence or absence, and changes to its thickness across the season. The Tibbitt to Contwoyto Winter Road has an average annual operating season of 67 days, meaning that even small delays in ice-on dates, or slightly earlier ice-off dates, can significantly impact the number of loads successfully transported. For example, an abnormally short operating season in 2005-2006 resulted in over 1200 loads needing to be flown to the mines sites during the summer season (Tibbitt to Contwoyto Winter Road Joint Venture, n.d.). The road also requires the ice to be at least 0.7 m thick to open operations, so even minor changes to the rate of growth across the season can lead to lost operation time. Both factors must be considered together when discussing future conditions.

CLIMo results suggest that of the net season shortening projected, more days will be lost from the end of the season (due to earlier ice-off dates) than from the beginning of the season (due to later ice-on dates), although a shortening is predicted from both sides. This trend is well-supported by other studies within the field (Dibike et al. 2011; Liston and Hall 1995; Ménard et al. 2002), and agrees with the current understanding of lake ice dynamics. Ice-off events are more sensitive to immediate air surface temperature changes (Bonsal et al., 2006), while ice-on is closely related to lake size and stored energy, which is associated with climatic conditions earlier in the season (Rouse et al. 2005). Because ice-on timing is combination of several factors, it may respond more slowly to future variability, as all factors continue to evolve and change under new climatic conditions.

The insulating influence of snow is also pronounced in the comparison between 1961-1990 and 2041-2070. Snow presence or absence is only a small factor, if at all, in the ice-on projections (snow can’t interact with ice that hasn’t yet formed), however, CLIMo results do show slight differences in ice-on dates for 3 m lakes with and without snow cover. These minor discrepancies may be attributable to computational errors; alternatively, CLIMo simulates even ice growth across theoretical lakes, as opposed to in nature where ice growth typically starts at the lake edge and comes to cover the entire lake surface over a period of several days, depending on lake size. The impact of snow on ice-off can be substantial. In simulations across both lake depths, when snow was present on the ice surface, ice-off was projected to occur between 5-12 days earlier compared to the baseline period; when snow was removed from the ice surface, ice-off was projected to occur 9-14 days earlier. Snow and snow removal is significant to road construction from an engineering standpoint; the snow layer is often removed from road surfaces to expose the ice to cold air masses above to increase thickness more quickly by reducing insulation from conductive heat loss due to large temperature gradients. Removing the snow layer in a warmer climate scenario will have impacts across most phenological indicators, to differing effect. There are potential impacts for maximum ice thickness but lake ice sensitivity studies suggest that small increases in air temperatures have minimal impacts on thickness during the coldest months of the year (Ménard et al., 2002). However, Weyenmeyer (2004) demonstrates that at latitudes relevant for this study, even a one-degree increase in spring air temperatures can accelerate ice-off events by several weeks, which may call into question one of the most basic and cost-effective ice engineering techniques in use along the TCWR today.

Lake size is also an important consideration in this type of study. Increases to summer and fall air temperatures have the potential to influence ice phenologies based on lake size in two primary ways: first, smaller, shallower lakes, such as the lakes along the TCWR, which have an average depth of less than 8 m (Pienitz et al., 1997), are more sensitive to climate variability and temperature changes due to their smaller heat storage potential (Rouse et al., 2005; 2008; Oswald et al., 2008). These small lakes will be more sensitive to temperature changes predicted by the CRCM, which will likely be reflected in their relatively large sensitive heat flux terms when compared to larger lakes. However, because of the low heat storage potential of small lakes, smaller lakes also lose heat energy more quickly in the fall towards the ice-on period as air temperatures drop quickly, leading to relatively minor delays in ice-on events. While the TCWR is predominantly built upon small, shallow lakes, there are larger, deeper lakes along the route with a much greater potential to store the heat energy generated by increases in summer air temperatures. Therefore, the greatest delays to ice-on and road opening events will likely be seen on the larger lakes on route, for which the sensible and latent heat fluxes are still active until later in the year, delaying ice formation. The significance of lake size is negligible, however, during ice-off, where there is little relationship to a lake's heat storage potential; lake ice breaks up fairly uniformly across the size gradient as regional temperatures warm (Bonsal et al. 2002; 2006)

Changes in ice thickness

Given our understanding that ice thickness can be strongly influenced by snow cover given equivalent surface air temperatures, simulating ice growth with and without and snow layer is important for determining the sensitivity of this relationship. As well, while our understanding of changing arctic temperature regimes is reasonably well understood, there remains more uncertainty when forecasting changes to precipitation patterns. The most recent Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5) furthers the widely held belief that arctic precipitation will increase in the near future, and that most winter (December–February) precipitation will continue to fall as snow (IPCC, 2013).

CLIMo includes a snow ice formation parameterization, and the ability to remove the snow layer improves our ability to understand the interplay between climatic factors, but the presence or absence of snow, and changes to future snowfall patterns, considerably complicates future projections. Ice growth is a delicate balance between temperature and precipitation, as well as secondary climatic variables such as wind patterns which affect where and how snow accumulates on a landscape (Liston and Hall, 1995a; 1995b). Changes in wind patterns in particular are not well understood at present. Ice growth is also known to be highly sensitive to a variety of environmental factors, including lake latitude and seasonality and the timing of climatic anomalies (Weyenmeyer et al., 2004).

CLIMo results project a decrease in maximum ice thickness across all lake sizes and latitudes, with a strong thinning trend detected on ice surfaces without a snow layer (0.15-0.31 m, compared to 0.27-0.30 m). However, even though a greater thinning will be observed on ice surfaces without snow cover, the maximum thickness achieved is still projected to be thicker for ice surfaces without snow than ice surfaces with a snow layer (maximum ice thicknesses of 1.13-1.38 m compared to 1.58-2.00 m) (Figure 3-10), which remains relevant to the question of the significance of snow removal as an engineering technique. As mentioned previously, snow is an important consideration when discussing road construction. It is removed from the ice surface as an engineering technique to naturally increase ice thickness, but as the results show, ice surfaces without snow cover are more sensitive to future warming than ice with a modeled snow layer. This has the potential to reduce the efficacy of a foundation road engineering practice.

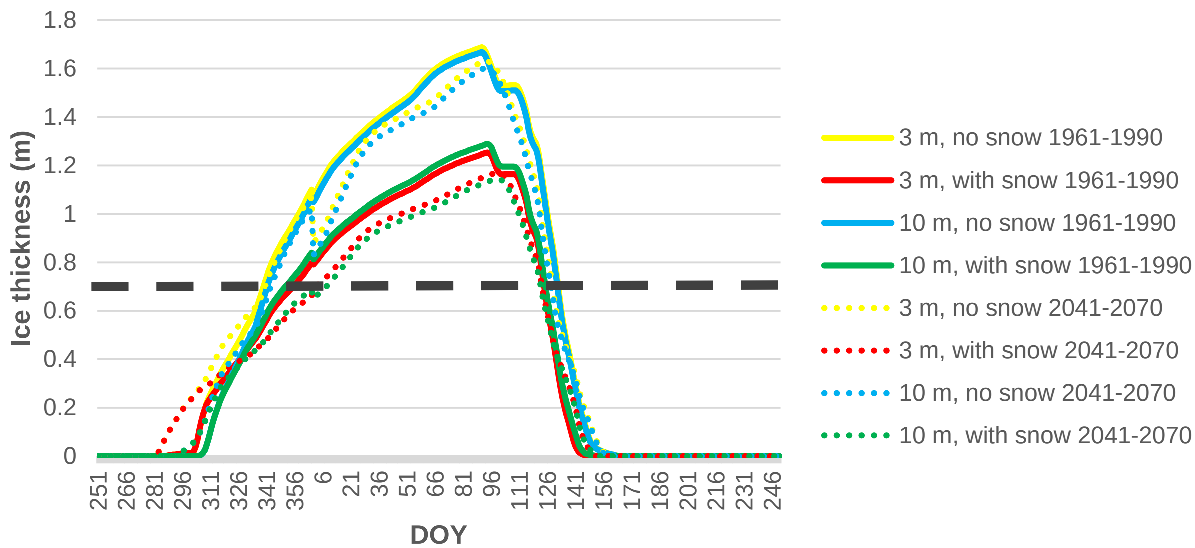


FIGURE 3-10: CLIMo–CRCM-simulated ice growth and decay for all depth and snow cover scenarios, showing projected changes between the 1961-1990 baseline and the 2041-2070 future scenario. The 0.7 m threshold is shown as a thick dashed line.

Implications for future road construction

While the present chapter discusses the future of the ice surfaces of the Tibbitt to Contwoyto Winter Road in terms of very general trends, it is acknowledged that this type of information is of mixed usefulness for day-to-day operational planning. When forced with CRCM inputs, CLIMo results suggest a decrease in ice cover season duration and ice thickness which can be extrapolated to suggest a shortening of the road operation season (roughly approximated as the period for which ice thickness exceeds 0.7 m), but the degree to which this may occur remains uncertain. What also remains uncertain is the threshold at which climate-induced shortenings of the operating season make building the TCWR economically unfeasible. Few studies currently exist to this effect. Notably, Stephenson et al. (2012) attempt to answer this question on the pan-arctic scale by using a transportation model integrating climate model outputs for air temperatures and snow depth, as well as topographic and built infrastructure information. Instead of results presented in terms of changes to physical ice surfaces as in this study, changes are measured as the difference in travel time between settlements, and the total area potentially accessible for overland transportation, finding a net decrease in the TCWR season of 17 per cent by 2020. Stephenson et al. (2012) parameterize winter road suitability as occurring when lake ice surfaces exceed 0.22 m (defined as the thickness needed to support a 2000 kg vehicle) and snow cover exceeds 0.20 m. While the model is not parameterized for the study of heavy duty industrial roads, and does not directly address the question of when the TCWR or any other ice roads across the region will become too expensive to construct, it does take the analysis a step further to add an operational element to the discussion of future ice road utility.

Another important consideration to be addressed in future planning studies is variability within the ice presence-absence question. In particular for planning purposes, it is important to understand when in the season more variability may be observed (e.g. during ice-off or ice-on), as well as the degree of variability within the lake size gradient, across latitudes, and across time. Stephenson et al. (2012) again attempt to answer these questions, projecting the greatest variability in travel time to occur in November and April, the shoulder seasons where temperatures fluctuate most closely around 0C. The ERA-Interim reanalysis data allows this level of analysis to take place on the historical simulations, but to facilitate such fine-scale temporal analysis for future periods, CLIMo would need to be forced with more highly representative climatic data known to be accurate on small time steps, a limitation of the CRCM 30-year mean periods used for this study.

3.5 Summary and conclusions

This study effectively shows that ice surfaces of the Tibbitt to Contwoyto Winter Road (TCWR) have changed in the recent historical period, and will in all likelihood continue to change at a similar or accelerated rate into the near future. By using an extensively validated lake ice model, the study is able to quantify changes to ice-on and ice-off dates, net changes to the ice cover season, and maximum ice thickness, both historically and for the near future. By forcing the Canadian Lake Ice Model (CLIMo) with ERA-Interim reanalysis data for the known operations period of 1982-2011, changes are observed across four indicators of ice conditions: ice-on dates are shown to shift later in the year by up to 3.9 days, and ice-off dates are shown to shift earlier in the year by up to 5.3 days, depending on lake depth and the presence or absence of simulated snow cover. A net shortening of the ice cover season is suggested by up to 14.4 days, depending on the model run, and shown to be statistically significant for simulations on 3 m lakes with snow cover, and 10 m lakes with and without simulated snow cover. Maximum ice thickness achieved over the season was shown to decrease by up to 0.17 m; the results were shown to be statistically significant for both 3 m and 10 m lakes with simulated snow cover.

When CLIMo is forced with Canadian Regional Climate Model (CRCM) output to facilitate projections of future ice conditions, results suggest that the shortening of the ice season and decrease in maximum ice thickness will continue into the near future. When a 1961-1990 baseline period is compared against a 2041-2070 future scenario, the study finds that ice-on dates are projected to shift later into the year by 4-11 days; ice-off events are projected to occur earlier in the year by 5-14 days; a net shortening of the ice season is projected on the order of 12-24 days; and maximum ice thickness is projected to decrease by 0.15-0.30 m (all results dependent on lake depth and snow cover scenario). In both the historical and future projections, ice-on is shown to be driven primarily by lake depth, as a function of the energy storage potential of the water. Ice-off events occur almost independent of lake size, and instead are driven by surface air temperatures, and affected marginally by the presence or absence of snow on the ice, as a function of its insulating properties. Maximum ice thickness is controlled primary by snow cover, again due to the insulating properties of snow on ice.

While the study is a good starting point for evaluating the future of ice road transportation in the Canadian arctic, as well as how it has changed in the recent past, there are some limitations in the data that may reduce the utility of the results. First, while CLIMo is understood to represent ice conditions well when accurate climatological inputs are used, projecting future climates in arctic regions via current modeling frameworks still proves challenging. This is less of an issue for the historical reconstructions; the ERA-Interim product has been well-validated and found to capture arctic climate well. However, temperature biases have been identified in CRCM outputs on several occasions; they were corrected for in this paper, but without greater areal weather station coverage, it remains an imperfect solution. Second, because of the uncertainties with the inputs for future projections, uncertainties remain regarding inter- and intra-annual variability, which is extremely relevant from an operations standpoint. While the current approach lends evidence that ice surfaces along the TCWR will likely see shorter seasons and thinner cover by late 21st century, a road manager is more likely to be concerned with how the ice will respond to climate changes in the next months, or next year, rather than in a hypothetical future. Unfortunately the nature of the CRCM inputs do not allow for analysis on such fine time scales. Relatedly, the use of the CRCM inputs and the need to combine results into 30-year mean periods limited our understanding of how the growth curves of the ice will change over time. The study focuses on changes to ice-on and ice-off dates, and the discussion approximates road open and close dates as the dates when ice thickness exceeds 0.7 m, however this is an imprecise analysis. For example, it remains unclear if the road operation season will reduce in days proportionally to the total ice cover season, or if the decreased ice thickness projected will mean that the road will lose even more operating days. Finally, the lack of in situ ice thickness data, or observations surrounding ice-on and ice-off events, make validating model outputs a challenge. For future studies, collecting ground measurements specific to the variables in question would be beneficial; for this study it was possible to rely on previous validation experiments, but if the nature of this work gets more specific, better data will be needed. In sum, future works would benefit from the use of more representative climate model inputs to project future ice conditions (e.g. the use of regional climate model ensembles), with more comprehensive climatological validation data and ice observations along the route.

Finally, despite the limitations discussed previously, the study does contribute to a knowledge area where little research has traditionally been focused. It has been often acknowledged, but not quantified, that ice road utility may decrease in a warmer climate, and the study corroborates this understanding. However, there are considerations to the findings. First, despite the accelerating warming occurring in arctic regions, freshwater ice is not projected to disappear completely in the near future, and changes to ice cover duration and thickness are statistically significant, but relatively small in magnitude. As long as ice exists on arctic lakes and rivers, some capacity for overland transport will remain, either in the form of shorter shipping seasons corresponding to shorter ice cover seasons, or smaller loads due to safety concerns with a thinner ice cover. As well, because of the incremental changes observed and projected for the region, it is not unreasonable to expect that the mines the TCWR serves will reach the end of their working life cycles before road-ending ice changes occur; however, the results of this study suggest that many other ice roads in the region may be at risk for ice surfaces changes as well. The roads need to be studied on a case by case basis to ensure the safety of the operators who use them, but the need for this type of transportation will not be diminished as activity in the north increases. Relatedly, as arctic activity increases, the need for overland transportation will only increase proportionally, and if ice roads become in general less useful for much of the year, the need for reliable all-season roads will increase as well.

CHAPTER 4: SUMMARY AND CONCLUSIONS

This thesis contributes to the field of arctic climate change research by quantifying historical and projected changes to lake ice cover significant for ice road construction. Ice roads are an important means of transportation in the Canadian arctic, and are often the only option for overland transportation for remote communities and resource extraction projects. The Canadian sub-arctic is a water-rich landscape, dominated by lakes and wetlands, which makes building all-season roads a challenge, and in many cases infeasible and economically inefficient. Understanding how ice cover is projected to change is important from a scientific perspective, as well as for planning purposes as development in the north continues at an accelerated pace.

The Tibbitt to Contwoyto Winter Road (TCWR) was selected as a case study due to its size and economic significance, but over 2, 000 km of seasonal roads are currently in use across the Northwest Territories alone; the results of this study are broadly applicable, and suggest that the system as a whole may be challenged as the global climate continues to change. The climatic stresses on the ice road network will become especially relevant as political, economic, and industrial activity in the north continues to increase.

4.1 Summary of results

This thesis effectively shows that ice surfaces of the TCWR have changed in the recent historical period, and will in all likelihood continue to change at a similar or accelerated rate into the near future. The Canadian Lake Ice Model (CLIMo) was forced first with ERA-Interim atmospheric reanalysis data for the known operations period of 1982-2011 to facilitate the reconstruction and analysis of historical ice conditions, and second with Canadian Regional Climate Model (CRCM 4.2.0) for a 1961-1990 baseline period and 2041-2070 future scenario to facilitate a discussion surrounding projected changes to ice conditions due to climatic changes in the region.

By using CLIMo, the study is able to quantify changes in freeze-dates, ice-off dates, net changes to the ice cover season, and maximum ice thickness both historically and for the near future. By forcing CLIMo with ERA-Interim reanalysis data for 1982-2011, changes are observed across four key variables: ice-on dates are shown to shift later in the year by up to 3.9

days, and ice-off dates are shown to shift earlier in the year by up to 5.3 days, depending on lake depth and the presence or absence of simulated snow cover. A net shortening of the ice cover season is suggested, on the order of 2.9 days to 9.8 days, depending on the model run, and shown to be statistically significant for simulations on 10 m lakes with and without simulated snow cover. Maximum ice thickness achieved over the season was shown to decrease, by 0.11 m to 0.14 m; the results were shown to be statistically significant for both 3 m and 10 m lakes with simulated snow cover.

When CLIMo is forced with CRCM output to facilitate projections of future ice conditions, results suggest that the shortening of the ice season and decrease in maximum ice thickness will continue into the near future. When a 1961-1990 baseline period is compared against a 2041-2070 future scenario, the study finds ice-on dates are projected to shift later into the year by 4-11 days; ice-off events are projected to occur earlier in the year by 5-14 days; a net shortening of the ice season is projected on the order of 12-24 days; and maximum ice thickness is projected to decrease by 0.15-0.30 m (all results dependent on lake depth and snow cover scenario). In both the historical and future projections, ice-on is shown to be driven primarily by lake depth, as a function of the energy storage potential of the water. Ice-off events occur almost independent of lake depth, and instead are driven by surface air temperatures, and affected marginally by the presence or absence of snow on the ice, as a function of its insulating properties. Maximum ice thickness is controlled primary by snow cover, again due to the insulating properties of snow on ice. The implications of these projected changes on the TCWR are twofold: first, results suggest that the region is not in immediate danger of the ice surfaces losing enough thickness to bring them below the 0.7 m threshold for safe operations. If ice thickness is the only consideration for road planning, the TCWR can likely continue to be built well into the foreseeable future. Second, however, the changes to ice thickness are coupled with decreases to the ice season length, reducing the total time that the ice is thicker than 0.7 m. The TCWR costs an estimated $10 million to build, annually; for the project to continue to be an efficient means of moving materials and people to the mines, operators need to maximize the number of trips made, or volume of goods shipped, during the winter season. The average road season is already only 67 days (www.jvtcwr.com, n.d.); losing even a small proportion of the operations season, as could be inferred by the CLIMo–CRCM results, could strike a significant blow to the economic feasibility of continued road use. No written work exists, and road managers were unwilling to comment on the threshold at which point building the TCWR every year becomes more costly than other alternatives.

4.2 Study limitations

While the study is a good starting point for evaluating the future of ice road transportation in the Canadian arctic, there are some notable limitations in the methods that reduce the utility of the results. First, while CLIMo is understood to represent ice conditions well when accurate climatological inputs are used, projecting climatic changes in arctic regions via current modeling frameworks still proves challenging. This is less of an issue for the historical reconstructions; the ERA-Interim product has been well-validated and found to capture arctic climate well. However, temperature biases have been identified in CRCM 4.2.0 outputs on several occasions; they were corrected for in this thesis, but without greater areal met station coverage, it remains an imperfect solution. Second, because of the uncertainties with the inputs for future projections, uncertainties remain regarding inter- and intra-annual variability, which is extremely relevant from an operations standpoint. While the current approach lends evidence that ice surfaces along the TCWR will likely see shorter seasons and thinner cover by late 21st century, a road manager is more likely to be concerned with how the ice will respond to climate changes in the next months, or next year, rather than in a hypothetical future. Unfortunately the nature of the CRCM inputs do not allow for analysis on such fine time scales. Relatedly, the use of the CRCM inputs and the need to combine results into 30-year mean periods limits our understanding of how the growth curves of the ice will change over time. The study focuses on changes to ice-on and ice-off dates, and approximates road open and close dates as the dates when ice thickness exceeds 0.7 m, however this is an imprecise analysis. For example, it remains unclear if the road operation season will reduce in days proportionally to the total ice cover season, or if the decreased ice thickness projected will mean that the road will lose even more operating days. Finally, the lack of in situ ice thickness data, or observations surrounding ice-on and ice-off events, make validating model outputs a challenge. For future studies, collecting ground measurements specific to the variables in question would be beneficial; for this study it was possible to rely on previous validation exercises, but if the nature of this work gets more specific, better data will be needed. Future works would benefit from the use of more representative climate model inputs to project future ice conditions, with more comprehensive climatological validation data and ice observations along the route.

4.3 Suggestions for future work

Finally, despite the limitations discussed previously, the study does contribute to a knowledge area where little academic work has traditionally been focused. It has been often acknowledged, but not quantified, that ice road utility may decrease in a warmer climate, and the study corroborates and improves on this understanding. However, there are considerations to the findings. First, despite the accelerating warming occurring in arctic regions, freshwater ice is not projected to disappear completely in the near future, and changes to ice cover duration and thickness appear to be smaller in magnitude than initially expected for the region of the TCWR. As long as ice exists on arctic lakes and rivers, some capacity for overland transport will remain, either in the form of shorter shipping seasons corresponding to shorter ice cover seasons, or smaller loads due to safety concerns with a thinner ice cover. As well, because of the incremental changes observed and projected for the region, it is not unreasonable to expect that the mines the TCWR serves will reach the end of their working life cycles before road-ending ice changes occur. However, the results of this study suggest that many other ice roads in the region may be at risk for ice surfaces changes as well, and changes to ice conditions in other regions may be larger than those projected in the region of the TCWR (Brown and Duguay, 2011). The roads need to be studied on a case by case basis to ensure the safety of the operators who use them, but the need for this type of transportation will not be diminished as activity in the north increases. Relatedly, as arctic activity increases, the need for overland transportation will only increase proportionally, and if ice roads become less useful for much of the year, the need for reliable all-season roads will increase as well.

There are many directions this project could take for future work. CLIMo appears to be a useful tool for studying localized ice conditions, and as such could be used to look at other important roads across different time scales and regions as needed. Work could also focus on improving the climatic inputs for the lake ice model; validation experiments suggest that CLIMo is only as accurate as its inputs, and increasing confidence in the climate change projections used for inputs would allow for analysis on much finer timescales, and enable discussions of variability, as opposed to just general trends. Also, more accurate inputs would enable future studies to move beyond discussing the ice season in general and instead focus on the road operating season, by transitioning away from identifying changes in ice-on and ice-off patterns and instead focus on changes to road open and close dates. Another strategy to achieve this goal may be to use CLIMo outputs to drive transportation or accessibility models (perhaps similar to Stephenson et al., 2012). Finally, a significant future contribution would be to take in situ thickness measurements along the road or roads in question to enable more substantial validation exercises to increase confidence in the results. Similarly, collaborating with road managers and operators could better integrate academic and industrial objectives and identify specific research questions relevant to operational objectives as opposed to from a purely academic point of view.

REFERENCE LIST

Adams, W.P., (1976). Diversity of lake cover and its implications, Musk-Ox Journal, 18: 86-98.

Adams, W.P., & Roulet, N.T., (1980). Illustration of the roles of snow in the evolution of the winter cover of a lake. Arctic, 33(1): 100-116.

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere.

Andrey, J., Kertland, P. and Warren, F.J. (2014): Water and transportation infrastructure; in Canada in a changing climate: sector perspectives on impacts and adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 233-252.

Ashton, G. D. (1985). Deterioration of Floating Ice Covers. *Journal of Energy Resources Technology*, *107*(June 1985), 177–182.

Bonsal, B. R., Prowse, T. D., Duguay, C. R., & Lacroix, M. P. (2006). Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over Canada. *Journal of Hydrology*, *330*(1-2), 340–353. doi:10.1016/j.jhydrol.2006.03.022

Brown, L. C., & Duguay, C. R. (2010). The response and role of ice cover in lake-climate interactions. *Progress in Physical Geography*, *34*(5), 671–704. doi:10.1177/0309133310375653

Brown, L. C., & Duguay, C. R. (2011). The fate of lake ice in the North American Arctic. *The Cryosphere*, *5*(4), 869–892. doi:10.5194/tc-5-869-2011

Corti, S., Molteni, F., & Palmer, T. N. (1999). Signature of recent climate change in frequencies of natural atmospheric circulation regimes, *398*(April), 799–802.

D.M. Lawrence, A. G. S. (2009). The contribution of snow condition trends to future ground climate. *Climate Dynamics*. Retrieved from The contribution of snow condition trends to future ground climate

Decker, M., Brunke, M. a., Wang, Z., Sakaguchi, K., Zeng, X., & Bosilovich, M. G. (2012). Evaluation of the Reanalysis Products from GSFC, NCEP, and ECMWF Using Flux Tower Observations. *Journal of Climate, 25*(6), 1916–1944. doi:10.1175/JCLI-D-11-00004.1

Dee, D. P., Uppala, S. M., Simmons, a. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. doi:10.1002/qj.828

Derksen, C., Smith, S. L., Sharp, M., Brown, L., Howell, S., Copland, L., … Walker, a. (2012). Variability and change in the Canadian cryosphere. *Climatic Change*, *115*(1), 59–88. doi:10.1007/s10584-012-0470-0

Duguay, C. R., Flato, G. M., Jeffries, M. O., Ménard, P., Morris, K., & Rouse, W. R. (2003). Ice-cover variability on shallow lakes at high latitudes: model simulations and observations. *Hydrological Processes*, *17*(17), 3465–3483. doi:10.1002/hyp.1394

Duguay, C. R., Prowse, T. D., Bonsal, B. R., Brown, R. D., Lacroix, M. P., & Ménard, P. (2006). Recent trends in Canadian lake ice cover. *Hydrological Processes*, *20*(4), 781–801. doi:10.1002/hyp.6131

Flato, G. M. (1996). Variability and climate sensitivity of landfast Arctic sea ice. *Journal of Geophysical Research*, *101*, 767–777.

GNWT Department of Transportation. (n.d.). Retrieved from http://www.dot.gov.nt.ca/

GNWT Mackenzie Valley Highway. (2013). Retrieved from http://inuviktotuk.dot.gov.nt.ca/

Holland, M. M., Bitz, C. M., & Tremblay, B. (2006). Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters*, *33*(23), L23503. doi:10.1029/2006GL028024

Jeffries, M. O., J. A. Richter-Menge, and J. E. O. (2013). *NOAA Arctic Report Card*. Retrieved from http://www.arctic.noaa.gov/reportcard.

Jiping Liu, Judith Curry, Huijun Wang, Miron Song, R. H. (2011). Impact of declining arctic sea ice on winter snowfall. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(11).

Laprise, R. (2008). Regional climate modelling. *Journal of Computational Physics*, *227*(7), 3641–3666. doi:10.1016/j.jcp.2006.10.024

Lesins, G., Duck, T. J., & Drummond, J. R. (2012). Surface Energy Balance Framework for Arctic Amplification of Climate Change. *Journal of Climate*, *25*(23), 8277–8288. doi:10.1175/JCLI-D-11-00711.1

Liston, G., & Hall, D. K. (1995). An energy balance model of lake ice evolution. *Journal of Glaciology*, *41*(138).

Mackay, M. D., Neale, P. J., Arp, C. D., Domis, L. N. D. S., Fang, X., Gal, G., … Stokes, S. L. (2009). Modeling lakes and reservoirs in the climate system, *54*, 2315–2329.

Macumber, A.L., Neville, L.A., Galloway, J.M., Patterson, R.T., Falck, H., Swindles, G.T., Crann, C., Clark, I., Gammon, P., Madsen, E. (2012). *NWT Open Report 2011-010 Paleoclimatological Assessment of the Northwest Territories and Implications for the Long-*

Term Viability of the Tibbitt to Contwoyto Winter Road , Part II : March 2010 Field Season Results NWT Open Report 2011-010.

Mahlstein, I., & Knutti, R. (2012). September Arctic sea ice predicted to disappear near 2°C global warming above present. *Journal of Geophysical Research*, *117*(D6), D06104. doi:10.1029/2011JD016709

McGregor, R. V., Hassan, M., & Hayley, D. (2008). Climate change impacts and adaptation: case studies of raods in Northern Canada. In *2008 Annual Conference of the Transportation Association of Canada* (pp. 1–15). Toronto.

Ménard, P., Duguay, C. R., Pivot, F. C., Flato, G. M., & Rouse, W. R. (2002). Sensitivity of Great Slave Lake ice phenology to climate change. Ice in the environment: Proceedings of the 16th IAHR International Symposium on Ice, Dunedin, New Zealand, 2nd-6th December, 2002.

Mesher, D. E., Ph, D., Presenter, P. E., & Madsen, E. (2008). Ice Road Assessment , Modeling and Management Paper prepared for presentation at the Impact of Climate Change on Infrastructure Construction , Maintenance and Operations Session of the 2008 Annual Conference of the Transportation Association of Canada Tor, 1–20.

Ménard, P., Duguay, C. R., Flato, G. M., & Rouse, W. R. (2002). Simulation of ice phenology on Great Slave Lake, Northwest Territories, Canada. *Hydrological Processes*, *16*(18), 3691–3706. doi:10.1002/hyp.1230

Moritz, R. E., Bitz, C. M., & Steig, E. J. (2002). Dynamics of recent climate change in the Arctic. *Science (New York, N.Y.)*, *297*(5586), 1497–502. doi:10.1126/science.1076522

Oswald, C. J., & Rouse, W. R. (2004). Thermal Characteristics and Energy Balance of Various-Size Canadian Shield Lakes in the Mackenzie River Basin. *Journal of Hydrometeorology*, *5*(1), 129–144. doi:10.1175/1525-7541(2004)005<0129:TCAEBO>2.0.CO;2

Overland, J. E., & Wang, M. (2013). When will the summer Arctic be nearly sea ice free? *Geophysical Research Letters*, *40*(10), 2097–2101. doi:10.1002/grl.50316

Pienitz, R., Smol, J. P., & Lean, D. R. (1997). Physical and chemical limnology of 24 lakes located between Yellowknife and Contwoyto Lake, Northwest Territories (Canada). *Canadian Journal of Fisheries and Aquatic Sciences*, *54*(2), 347–358. doi:10.1139/f96-275

Prowse, T., Alfredsen, K., Beltaos, S., Bonsal, B., Duguay, C., Korhola, A., … Weyhenmeyer, G. a. (2012a). Arctic Freshwater Ice and Its Climatic Role. *Ambio*, *40*(S1), 46–52. doi:10.1007/s13280-011-0214-9

Prowse, T., Alfredsen, K., Beltaos, S., Bonsal, B., Duguay, C., Korhola, A., … Weyhenmeyer, G. a. (2012b). Arctic Freshwater Ice and Its Climatic Role. *Ambio*, *40*(S1), 46–52. doi:10.1007/s13280-011-0214-9

Prowse, T., Alfredsen, K., Beltaos, S., Bonsal, B. R., Bowden, W. B., Duguay, C. R., … Weyhenmeyer, G. a. (2012). Effects of Changes in Arctic Lake and River Ice. *Ambio*, *40*(S1), 63–74. doi:10.1007/s13280-011-0217-6

Prowse, T. D., Furgal, C., Chouinard, R., Melling, H., Milburn, D., & Smith, S. L. (2009). Implications of climate change for economic development in northern Canada: energy, resource, and transportation sectors. *Ambio*, *38*(5), 272–81. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19714960

Riche, F., & Schneebeli, M. (2013). Thermal conductivity of snow measured by three independent methods and anisotropy considerations. *The Cryosphere*, *7*(1), 217–227. doi:10.5194/tc-7-217-2013

Rouse, W. P., Chertzer, W. I. M. S., Lanken, P. E. D. B., Ussières, N. O. B., & Uguay, C. L. R. D. (2005). The Role of Northern Lakes in a Regional Energy Balance, 291–305.

Rouse, W. R., Blanken, P. D., Bussières, N., Walker, A. E., Oswald, C. J., Schertzer, W. M., & Spence, C. (2008). An Investigation of the Thermal and Energy Balance Regimes of Great Slave and Great Bear Lakes. *Journal of Hydrometeorology*, *9*(6), 1318–1333. doi:10.1175/2008JHM977.1

Serreze, M. C., & Barry, R. G. (2011). Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, *77*(1-2), 85–96. doi:10.1016/j.gloplacha.2011.03.004

Slater, A. G., & Lawrence, D. M. (2012). Diagnosing Present and Future Permafrost from Climate Models, 1–34.

Stephenson, S.R., Smith, L.C., and Agnew, J. A. (2012). Divergent long-term trajectories of human access to the Arctic. *Nature Climate Change*, *May 11 (pu*, 1–5.

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., & Barrett, A. P. (2011). The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change*, *110*(3-4), 1005–1027. doi:10.1007/s10584-011-0101-1

Stroeve, J., Holland, M. M., Meier, W., Scambos, T., & Serreze, M. (2007). Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters*, *34*(9), n/a–n/a. doi:10.1029/2007GL029703

Sturm, M. (2002). Thermal conductivity and heat transfer through the snow on the ice of the Beaufort Sea. *Journal of Geophysical Research*, *107*(C10), 8043. doi:10.1029/2000JC000409

Walsh, J. E., Overland, J. E., Groisman, P. Y., & Rudolf, B. (2012). Ongoing Climate Change in the Arctic. *Ambio*, *40*(S1), 6–16. doi:10.1007/s13280-011-0211-z

Wang, M., & Overland, J. E. (2009). A sea ice free summer Arctic within 30 years ? *Geophysical Research Letters*, *36*(April), 2–6. doi:10.1029/2009GL037820

Williams, G., Layman, K. L., & Stefan, H. G. (2004). Dependence of lake ice covers on climatic, geographic and bathymetric variables. *Cold Regions Science and Technology*, *40*(3), 145–164. doi:10.1016/j.coldregions.2004.06.010

Winton, M. (2006). Does the Arctic sea ice have a tipping point? *Geophysical Research Letters*, *33*(23), L23504. doi:10.1029/2006GL028017